NBSIR 79-1948

Optimizing Weatherization Investments in Low-Income Housing: Economic Guidelines and Forecasts

Robert E. Chapman, Richard W. Crenshaw,
Kimberly A. Barnes, and Phillip T. Chen

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

February 1980

Final Report

Sponsored by the:
Community Services Administration
1200 19th Street, NW
Washington, D.C. 20506

NBSIR 79-1948

OPTIMIZING WEATHERIZATION INVESTMENTS IN LOW-INCOME HOUSING: ECONOMIC GUIDELINES AND FORECASTS

Robert E. Chapman, Richard W. Crenshaw,
Kimberly A. Barnes, and Phillip T. Chen

Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

February 1980

Final Report

Sponsored by the:
Community Services Administration
1200 19th Street, NW
Washington, D.C. 20506

U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*

Luther H. Hodges, Jr., *Deputy Secretary*
Jordan J. Baruch, *Assistant Secretary for Productivity, Technology, and Innovation*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

This research was conducted under the sponsorship of the Community Services Administration by the Applied Economics Group of the Center for Building Technology, National Engineering Laboratory, National Bureau of Standards.

The burden of rapidly rising energy costs on low-income families has prompted concern for the health and well-being of low-income Americans and led to the passage of Public Laws 93-644 and 94-385. These laws establish energy conservation (weatherization) programs for low-income families and provide funds for weatherization grants. Under Public Law 93-644 Congress has assigned to the Community Services Administration (CSA) the leadership role in reducing the energy cost burden on low-income Americans. The Community Services Administration's Weatherization Demonstration Program carried out through the National Bureau of Standards as one of its objectives an estimate of how much money can be saved through optimum weatherization.

This report establishes a framework for systematically analyzing alternative methods of weatherizing low-income housing, and provides forecasts of the optimal level of weatherization for the 15 cities participating in the Community Services Administration's Weatherization Demonstration Program. Data collected during the Weatherization Demonstration Program will facilitate the testing and refinement of these forecasts.

Appreciation is extended to Drs. Harold E. Marshall and Stephen F. Weber, Applied Economics Group, and Mr. William G. Hall, Center for Applied Mathematics, who reviewed the economics and mathematical aspects of the paper. Special appreciation is extended to Dr. Joseph G. Kowalski and Mr. Stephen R. Petersen, Applied Economics Group, for their helpful comments throughout the course of this research effort. Special appreciation is also extended to Dr. Alan J. Goldman, formerly of the Center for Applied Mathematics, and Mr. Harvey W. Berger, National Engineering Laboratory, for their excellent suggestions on the treatment of certain technical aspects presented in the paper. Special appreciation is also extended to Ms. Barbara C. Cassard, Applied Economics Group, who performed most of the computer calculations.

ABSTRACT

This study establishes a framework for systematically analyzing the economic viability of alternative methods of weatherizing low-income housing. These methods include but are not limited to insulation, weatherstripping and caulking, and installation of storm windows and doors. The economic framework is illustrated through the development of a series of forecasts (economic guidelines) which show the optimal level of weatherization for low-income residences in 15 cities across the Nation. These economic guidelines are designed to assist the Community Services Administration in carrying out its Weatherization Demonstration Program. In particular, they are designed to achieve a more balanced level of weatherization per dollar spent. The optimal level of weatherization is balanced in the sense that for a given weatherization budget no increases in net savings (total savings minus total costs) can be achieved by trading one method for another.

Key Words: Benefit-cost analysis; building economics; building envelope; economic analysis; economic efficiency; energy conservation; insulation; life-cycle costs; low-income housing; marginal analysis; thermal efficiency; weatherization.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF EXHIBITS

LIST OF TABLES

Page

Page

MOST COMMON SI UNITS AND THEIR EQUIVALENT VALUES IN CUSTOMARY UNITS

QUANTITY	INTERNATIONAL (SI) UNIT	U.S. CUSTOMARY UNIT	APPROXIMATE CONVERSION	
LENGTH	meter (m)	foot (ft)	1 m	= 3.2808 ft
	millimeter (mm)	inch (in)	1 mm	= 0.0394 in
AREA	square meter (m^2)	square yard (yd^2)	1 m^2	= 1.1960 yd^2
		square foot (ft^2)	1 m^2	= 10.764 ft^2
	square millimeter (mm^2)	square inch (in^2)	1 mm^2	= 1.5500×10^{-3} in^2
VOLUME	cubic meter (m^3)	cubic yard (yd^3)	1 m^3	= 1.3080 yd^3
		cubic foot (ft^3)	1 m^3	= 35.315 ft^3
	cubic millimeter (mm^3)	cubic inch (in^3)	1 mm^3	= 61.024×10^{-6} in^3
CAPACITY	liter (L)	gallon (gal)	1 L	= 0.2642 gal
	milliliter (mL)	fluid ounce (fl oz)	1 mL	= 0.0338 fl oz
VELOCITY, SPEED	meter per second (m/s)	foot per second (ft/s or f.p.s.)	1 m/s	= 3.2808 ft/s
	kilometer per hour (km/h)	mile per hour (mile/h or m.p.h.)	1 km/h	= 0.6214 mile/h
ACCELERATION	meter per second squared (m/s^2)	foot per second squared (ft/s^2)	1 m/s^2	= 3.2808 ft/s^2
MASS	metric ton (t) [1000 kg]	short ton [2000 lb]	1 t	= 1.1023 ton
	kilogram (kg)	pound (lb)	1 kg	= 2.2046 lb
	gram (g)	ounce (oz)	1 g	= 0.0353 oz
DENSITY	metric ton per cubic meter (t/m^3)	ton per cubic yard (ton/yd^3)	1 t/m^3	= 0.8428 ton/yd^3
	kilogram per cubic meter (kg/m^3)	pound per cubic foot (lb/ft^3)	1 kg/m^3	= 0.0624 lb/ft^3
FORCE	kilonewton (kN)	ton-force (tonf)	1 kN	= 0.1124 tonf
		kip [1000 lbf]	1 kN	= 0.2248 kip
	newton (N)	pound-force (lbf)	1 N	= 0.2248 lbf
MOMENT OF FORCE, TORQUE	kilonewton meter (kN•m)	ton-force foot (tonf•ft)	1 kN•m	= 0.3688 tonf•ft
	newton meter (N•m)	pound-force inch (lbf•in)	1 N•m	= 8.8508 lbf•in
PRESSURE, STRESS	megapascal (MPa)	ton-force per square inch ($tonf/in^2$)	1 MPa	= 0.0725 $tonf/in^2$
		ton-force per square foot ($tonf/ft^2$)	1 MPa	= 10.443 $tonf/ft^2$
	kilopascal (kPa)	pound-force per square inch (lbf/in^2)	1 kPa	= 0.1450 lbf/in^2
		pound-force per square foot (lbf/ft^2)	1 kPa	= 20.885 lbf/ft^2
WORK, ENERGY, QUANTITY OF HEAT	megajoule (MJ)	kilowatthour (kWh)	1 MJ	= 0.2778 kWh
	kilojoule (kJ)	British thermal unit (Btu)	1 kJ	= 0.9478 Btu
	joule (J)	foot pound-force (ft•lbf)	1 J	= 0.7376 ft•lbf
POWER, HEAT FLOW RATE	kilowatt (kW)	horsepower (hp)	1 kW	= 1.3410 hp
	watt (W)	British thermal unit per hour (Btu/h)	1 W	= 3.4121 Btu/h
		foot pound-force per second (ft•lbf/s)	1 W	= 0.7376 ft•lbf/s
COEFFICIENT OF HEAT TRANSFER [U-value]	watt per square meter kelvin (W/m^2•K) [= (W/m^2•°C)]	Btu per square foot hour degree Fahrenheit (Btu/ft^2•h•°F)	1 W/m^2•K	= 0.1761 Btu/ft^2•h•°F
THERMAL CONDUCTIVITY [k-value]	watt per meter kelvin (W/m•K) [= (W/m•°C)]	Btu per square foot degree Fahrenheit (Btu/ft^2•°F)	1 W/m•K	= 0.5778 Btu/ft^2•°F

NOTES: (1) The above conversion factors are shown to three or four places of decimals.

(2) Unprefixed SI units are underlined. (The kilogram, although prefixed, is an SI base unit.)

REFERENCES:
- NBS Guidelines for the Use of the Metric System, LC1056, Revised August 1977;
- The Metric System of Measurement, Federal Register Notice of October 26, 1977, LC 1078, Revised November 1977;
- NBS Special Publication 330, "The International System of Units (SI)," 1977 Edition;
- NBS Technical Note 938, "Recommended Practice for the Use of Metric (SI) Units in Building Design and Construction," Revised edition June 1977;
- ASTM Standard E621-78, "Standard Practice for the Use of Metric (SI) Units in Building Design and Construction," (based on NBS TN 938), March 1978;
- ANSI Z210.1-1976, "American National Standard for Metric Practice;" also issued as ASTM E380-76[ε], or IEEE Std.268-1976.

1.0 INTRODUCTION

As a result of the "energy crisis," American consumers have become acutely aware that energy prices are rising rapidly and that substantial real[1] energy price increases are likely to persist well into the future. Low-income homeowners, unlike other consumers, often spend a disproportionate share of the family budget on housing services including energy. Increasing housing expenditures therefore tend to act as a regressive tax, forcing low-income homeowners to reduce their consumption of essentials such as food and clothing. Concern for the health and well-being of low-income Americans led to the passage of Public Law 93-644 in 1975 and of Public Law 94-385 in 1976. These laws establish energy conservation programs for low-income families and provide funds for weatherization grants.[2] Under Public Law 93-644 Congress has delegated to the Community Services Administration (CSA) the leadership role in administering a nationwide program to evaluate how much money can be saved through optimum weatherization.

A program has been undertaken in order to identify and test the optimum weatherization levels for different climatic regions of the country and for different supply and demand factors in the energy and construction sectors. Through this demonstration program, low-income residences will be weatherized at selected sites across the country. Explicit in this program is an economic analysis of alternative methods for weatherization. Since improving the efficiency of space heating systems and increasing the thermal resistance of the building envelope are nearly perfect substitutes for energy consumption,[3] it is necessary to weigh the costs of weatherization against future reductions in energy consumption. In particular, it is necessary to recognize that, other things being equal, each additional increase in the level of weatherization will generate smaller reductions in energy consumption. This implies that the economically optimal level of weatherization, i.e., the one which results in the maximum net savings (the excess of life-cycle savings over life-cycle costs[4]) will typically not coincide with the one which minimizes energy consumption.

---

[1] A real rate is a dollar value expressed in terms of constant purchasing power; in this case current dollar values have been adjusted to take out the reduction in purchasing power due to inflation.

[2] Throughout this report the term weatherization will be used synonymously with energy conservation.

[3] Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

[4] Life-cycle savings and costs will be discussed in detail in Chapter 3 of this report.

As energy prices continue to rise, low-income homeowners may find that weatherization is one of the best investment opportunities available. Even at today's borrowing rates, consumers are wise to invest in energy conservation. Subsidized programs could therefore provide an incentive to low-income homeowners to weatherize. Furthermore, most weatherization options can pay for themselves over the term of the usual home improvement loan. Low-income homeowners would therefore have a chance to reap permanent increases in future consumption of non-energy goods without drastically reducing their consumption of essentials in the present and near future. Weatherization investments also act as a hedge against inflation which severely impacts low-income families, especially if they are living on fixed incomes.

1.1 PURPOSE

The purpose of this study is to develop a framework which may be used by researchers and regional and local program managers of the CSA for systematically analyzing the economic viability of alternative methods of weatherizing low-income housing. Included in this framework is a forecast of the optimal level of weatherization for each demonstration site. These economic guidelines should enable representatives of the CSA, and other public administrators, to achieve a more balanced level of weatherization per dollar spent. The optimal level of weatherization is balanced in the sense that for a given weatherization budget no increases in net savings can be achieved by trading one method for another.

1.2 SCOPE AND APPROACH

The focus of this study is on identifying the optimal level of weatherization investment for each site in CSA's national demonstration program. The alternative methods for weatherization are divided into six basic categories. These categories were chosen in a such a way that each building element could be analyzed. The six weatherization categories studied are: (1) infiltration options; (2) window options; (3) door options; (4) attic insulation; (5) wall insulation; and (6) basement insulation. The study explicitly takes into consideration not only the present cost of energy and energy conservation but also future expenditures for energy, including projected real rates of energy price escalation. Anticipated costs resulting from the need to replace one or more weatherization options are also handled within the framework of the economic analyses.

It is important to note that the forecasts of the optimal level of weatherization for each demonstration site are based on life-cycle costs and savings. Therefore, in order to test or validate the forecasts made in this report, it will be necessary to analyze statistically data on the actual costs experienced in the field as well as pre and post weatherization energy consumption. This report, in its focus on forecasting the optimal level of weatherization, does not offer detailed statistical analyses of data from the demonstration sites. Statistical analyses of these data when they become available will be presented in a future report.

The basic format of the study consists of a description of CSA's weatherization demonstration program, the formulation of an economic model, and a presentation of the forecast of the economically optimal levels of weatherization for each demonstration site. Specifically, the study is organized as follows:

Chapter 2 describes the weatherization demonstration program, how the sites were selected, and which building types were chosen for study.

Chapter 3 develops a methodology for calculating weatherization costs and savings.

Chapter 4 presents the forecast of optimal weatherization for each demonstration site.

Chapter 5 contains a short summary of our research findings, and recommendations for future research including an econometric analysis of field weatherization costs.

The report also includes five technical appendices which treat in some detail: (A) the costs used in the economic analyses; (B) the methodology for estimating energy savings; (C) selected topics in investment theory which permit the economically optimal level of weatherization to be determined; (D) the computer program used to choose among weatherization methods; and (E) a summary of the calculations performed for each weatherization demonstration site.

2. DESCRIPTION OF THE WEATHERIZATION DEMONSTRATION PROGRAM

2.1 SITE SELECTION

The selection of the candidate cities for the demonstration program reflected a desire to assess accurately the effect of and relationships among as many key factors in the determination of weatherization savings as possible. Climate was judged to be the major determinant in the choice of the demonstration sites because it is the major variable affecting energy consumption and hence energy savings. By conducting demonstrations in a variety of climates it thus becomes possible to more efficiently estimate the savings attributable to an option or combination of options. The choice among alternative sites was simplified through an analysis of four key climatic parameters which affect buildings. These parameters are: (1) temperature; (2) humidity; (3) sunlight; and (4) wind.

Additional inputs to the selection process included results from The House Beautiful Climate Control Project[1] conducted by the American Institute of Architects and the Environmental Data Services' Climatic Atlas of the United States.[2] Major climatic zones were first identified with the Atlas which contains maps dividing the country into eleven temperature zones. Each zone corresponds to a "width" of 1000 degree days (see Figure 2.1).[3] These zones were used as a base map. Guidelines presented in The House Beautiful Climate Control Project were next used to subdivide the temperature zones on the base map. Candidate cities which best fit the two following requirements were then selected within each of these temperature zones. First, the city had to have CSA groups capable of meeting the needs of the program. Secondly, hourly climate data were available on tapes from the National Weather Service.

---

[1] American Institute of Architects, The House Beautiful Climate Control Project, Bulletin of the AIA, 1951.

[2] Environmental Data Service, Climatic Atlas of the United States, U.S. Department of Commerce Report, 1968, 1974.

[3] Degree days, DD, may be defined mathematically as

$$DD = \sum_{i=1}^{365} (65 - \overline{T}_i) \text{ for all } \overline{T}_i < 65$$

where $\overline{T}_i$ = the average temperature of the i^{th} day of the year.

Degree days are based on 65°F rather than 70°F, the assumed indoor temperature setting, since the 5°F temperature differential is considered to be provided by small solar radiation gains and internal heat sources rather than direct heating.

The 15 cities which were selected as demonstration sites are shown in Figure 2.1. The number of degree days for each city is given in parentheses by the city's name. No boundaries have been drawn around the climate zones surrounding each demonstration site. This is due primarily to difficulties involved in unambiguously identifying boundaries which are affected not only by the four climatic parameters mentioned above, but also by local factors such as mountains and large bodies of water. Consequently, it is recommended that the reader of this document not attempt to interpolate between sites. (Once post-retrofit information is available and analyzed this constraint may be relaxed. However, in the absence of firm empirical evidence the reader must be cautioned against generalizing the forecasts of optimum weatherization to other cities at different points in time.)

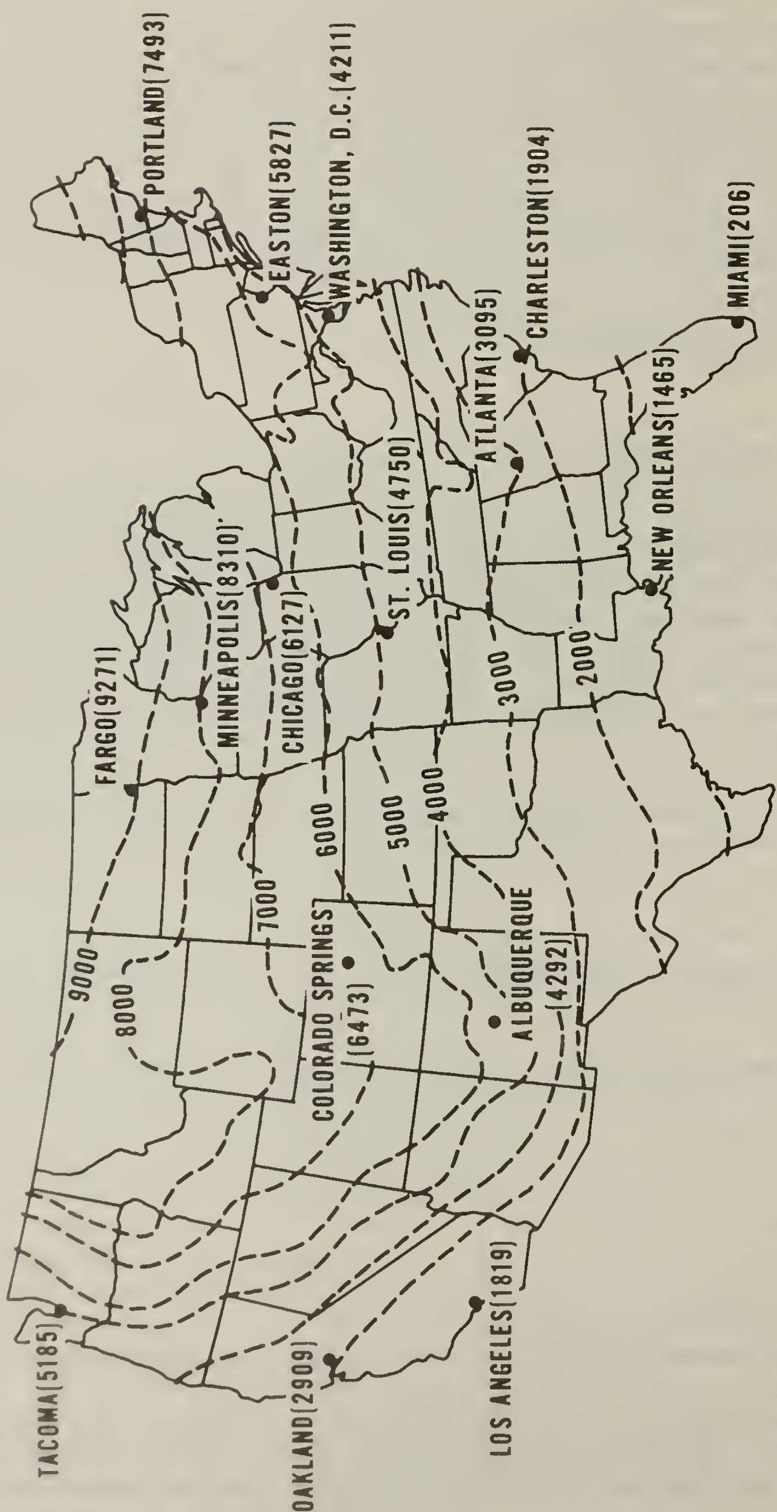
2.2 DWELLING UNIT SELECTION

The selction of dwelling units for inclusion in the demonstration program was based on the following considerations:

(1) the ability of the total sample of dwelling units to encompass those factors which affect energy consumption;
(2) the accuracy of the data on energy consumption;
(3) continued occupancy by the same family since April 1975;
(4) no major changes to the building's envelope or heating system since April 1975;
(5) that the building be in a reasonable state of repair; and
(6) that the building be of a fairly simple shape.

Based on these broad considerations, each demonstration site was requested to submit a sample of from 27 to 50 low-income residences which were typical of their locale. Additional factors were used to facilitate the selection of typical residences by the local CSA representatives. These factors are: (1) climate; (2) construction materials; (3) building type; (4) heating system type; (5) building size; (6) building shape; (7) building age; (8) percent of wall area in glass; (9) orientation; and (10) occupant characteristics. The first variable, climate, has already been addressed in the process of selecting the demonstration sites. Building shape was considered of minor importance. Building shapes were standardized in order to simplify energy load calculations and field test procedures. The remaining variables required closer attention so as to avoid the introduction of bias into the experiment. Of these eight variables, some will vary sufficiently across a sample of 27 to 50 dwelling units, some will vary moderately in any given cross section of low-income dwelling units, and some require a conscious effort to insure sufficient variation. Orientation, size, and occupant characteristics will usually vary sufficiently without special effort. The area of glass in low-income homes is normally between 20 and 30 percent of the wall area. Such a variation, though moderate, typifies most low-income houses. This leaves four factors which must be carefully "controlled" in the experiment. They are: building type, construction material, building age, and heating system type.

FIGURE 2.1 SELECTED SITES FOR WEATHERIZATION DEMONSTRATION PROGRAM



Sixteen cities are included on the map. This is because future weatherization activities are planned for New Orleans. The numbers shown on the map refer to heating degree days.

To facilitate the past retrofit analysis of energy savings, an experimental design which controlled for construction material and building type was formulated. This experimental design is reproduced in Table 2.1. The cities participating in the demonstration program are labeled at the top of each column of Table 2.1. The building type/construction material designator is labeled at the side of each row. Each block or "cell" in the experimental design lists the desired number of observations in the upper left half and the actual number of observations in the lower right half. For example, in Washington, D.C. the desired number of one story detached/wood frame houses was 5 where the actual number weatherized was 6. Those cases where the cell contains no entries indicate that the building type/construction material designator is atypical for that site. For example, the only site in which adobe homes are typical is Albuquerque. With respect to the heating system types, an even distribution of the types in the locality was requested. With respect to building age, each local CSA group was requested to submit at least two dwelling units from each of the following periods: pre World War I; between World War I and II; and post World War II.

The houses submitted by the local CSA representatives were then screened to ensure that each one had:

(1) accurate data on fuel consumption;
(2) the same occupants since April 1975;
(3) no major changes to the building's envelope or heating system since April 1975;
(4) been maintained in a reasonable state of repair; and
(5) a fairly simple shape.

For items 2, 3, and 4, it was necessary to rely on the on site evaluations by the local CSA representatives. Screening for item 5 involved a review of photographs submitted for each house. The screening for item 1 was more complicated and involved the use of the statistical techniques known as regression and correlation analysis. These techniques were used to evaluate the accuracy of the energy consumption data for individual dwelling units by examining the relationship (the ability to fit a straight line) between the quantity of fuel consumed and the number of degree days occurring between data points. More precisely, a linear relationship between energy consumption (gallons, therms, kilowatt hours) and degree days was hypothesized. Previous studies[1] have found this relationship to be valid. The linear relationship is extremely useful in estimating energy consumption for an individual dwelling unit. The relationship was empirically estimated by inputting values for actual energy use into a computer program. The best fit straight line was then identified using these data. (At least five readings are usually required to obtain the desired level of accuracy.) It was hypothesized that if the correlation

---

[1] L. S. Moyer and Y. Benjamin, "Modelling Residential Demand for Natural Gas as a Function of the Coldness of the Month," Energy in Buildings, Vol. VI, No. 3, April 1978.

TABLE 2.1 EXPERIMENTAL DESIGN FOR WEATHERIZATION DEMONSTRATION PROGRAM

BUILDING TYPE AND CONSTRUCTION MATERIAL	DEMONSTRATION SITES													
	Albuquerque	Atlanta	Charleston	Chicago	Colorado Spr.	Easton	Fargo	Miami	Minn./ St. Paul	Oakland	Portland	St. Louis	Tacoma	Washington
Detached (1) frame	5/5	5/5	5/6	5/4	5/12	5/5	5/13	5/6	5/6	5/6	5/4	5/3	5/5	5/6
Detached (2) frame				5/6	5/6	5/6			5/9		5/10	5/5		5/5
Detached (1) masonry	5/3	5/6	5/6					5/6		5/4		5/6		
Detached (1) adobe	5/3													
Detached (2) masonry												5/6		
Attached (2) masonry						5/6								
Detached (1) mas. veneer			5/5											
Detached (2) mas. veneer				5/5										

between actual energy consumption and degree days, as determined by the best fit straight line, exceeded 0.90 that the dwelling unit was acceptable for inclusion in the demonstration program. If the energy consumption data was unable to fit a straight line, it was taken as an indication of either maintenance problems not revealed in the field inspection or irrational responses to temperature or fuel price changes on the part of the homeowner. Those readers interested in a more detailed discussion of this topic are referred to Appendix E.

3.0 METHODS FOR CALCULATING WEATHERIZATION COSTS AND SAVINGS

It was mentioned earlier that the demonstration program has been undertaken in order to identify and test the optimum level of weatherization for different climatic regions of the country and for different supply and demand factors in the energy and construction sectors. The purpose of this chapter is to present a framework for: (1) choosing among alternative weatherization options and (2) selecting the level of investment for a given option which is economically most efficient.

From an economic standpoint, the goal of the demonstration is to identify and test that level of weatherization which maximizes net savings to the homeowner. These savings are associated with each weatherization option and are assumed to accrue over a period of 20 years. Consequently, both initial costs and savings and future costs and savings must be weighed. The background information which is required to calculate these weatherization savings and costs is discussed in this chapter. The technical underpinnings of the economic methodology which permits the optimal level of weatherization to be identified and tradeoffs among competing alternatives to be made is discussed in Appendix C.

3.1 OPTION COSTS

3.1.1 Initial Cost Considerations

In this report the definitions of initial costs to be used are fairly conventional. However, to insure understanding, we will explicitly define the terms which will be used throughout the report. For any particular weatherization task, a contractor will incur total a cost of undertaking that particular task. This total cost will include payments for labor, payments for materials, overhead costs and profits. The difference between the bid price (i.e., the contract amount for which the contractor agreed to do the work) and the total labor, materials, and overhead costs represents the contractor's pretax profits.

Those costs that the contractor incurs if he undertakes a specific job (i.e., labor costs including fringe benefits, social security, workmen's compensation, unemployment insurance,and the cost to the contractor for materials and equipment purchase/rental) are called direct costs. Labor costs, however, may be divided into two parts: 1) direct labor costs, and 2) indirect labor costs. Direct labor costs are those labor charges which can be associated with one particular weatherization option, such as scraping paint and caulking around windows. Indirect labor costs are those labor charges which can not be associated with any particular weatherization option but can be associated with a particular contract. For example, the time spent picking up building materials at a warehouse or lumber yard is in an indirect labor cost. Note that the direct cost for installing a weatherization option is by definition equal to the sum of the labor costs, material costs, and any special equipment costs.

Direct cost can be discussed either in total terms or in per unit terms. If we divide the total direct costs of installing 500 square feet of loose fill attic insulation by the number of square feet, we are then discussing direct costs per square foot (i.e., per unit direct cost). In this report our discussions of costs are presented on a per unit basis. Note that per unit direct cost is always equal by definition to the sum of per unit direct labor costs, per unit material costs, and any per unit special equipment costs.

Those costs that the contractor incurs regardless of whether he undertakes a specific job or not (e.g., rental payments, debt service payments, payments for equipment, payments for clerical and secretarial labor, and payments for management) are called overhead costs.

Another important factor is the size of the contractor's markup. The bid price divided by the sum of the direct costs in the contract yields one plus the percentage markup. Markup, therefore, includes both overhead costs and pretax profits. It is important to note that the overhead costs and profits which accrue to a specific task may depend on factors over and above that particular task. (For example, a lower percentage markup may be demanded if a contractor can install the entire weatherization package rather than only one or two options.[1])

3.1.2 Life-Cycle Cost Considerations

An interpretation of weatherization costs more comprehensive than initial costs is needed if the benefits of future energy savings are to be made comparable with the costs of weatherization. One approach which permits us to compare savings and costs unambiguously is the engineering economics concept of life-cycle costing.[2] Life-cycle cost techniques differ from initial cost considerations in that they explicitly take into account all costs (e.g., owning, operating, maintaining) which occur over the period under study. Thus if plastic storm windows were installed in a residence and due to a lack of long-term durability they had to be replaced every five years, then the value of the cash flows resulting from periodic replacement must be estimated. (These cash flows should in principle include any escalation in construction costs (labor, materials, and equipment) as well as incorporate a measure of the time value of money.[3])

---

[1] For a detailed discussion of markup and its determinants see Robert E. Chapman and Joseph G. Kowalski, Guidelines for Cost-Effective Lead Paint Abatement, National Bureau of Standards, Technical Note 971, Janaury 1979.

[2] Eugene L. Grant and W. Grant Ireson, Principles of Engineering Economy, Fifth Edition, The Ronald Press Company, New York, 1970.

[3] A more detailed treatment of prices changing over time and methods for comparing them on an equivalent basis is presented in Section 4.2 of this report.

Using the initial cost figure rather than the life-cycle cost figure would understate the true cost to the homeowner of using plastic storm windows for energy conservation purposes. To pursue this topic a bit further, suppose conventional storm windows have an estimated useful life of 20 years. Now if we assume that plastic storm windows have an estimated useful life of only five years but that both window systems save the same amount of energy over the 20 year period, then it is possible that plastic storm windows with their need for several replacements are more costly than conventional storm windows. (The value of energy being saved is the same.) Thus, only with life-cycle costing will the true costs of ownership over the study period be represented.[1] In this report life-cycle savings and costs will be used to compare alternative weatherization options. Additional assumptions concerning the relative performance and durability and how they affect the life-cycle costs of specific weatherization options are given in Section 4.2 and Appendix A of this report.

3.2 WEATHERIZATION SAVINGS

The calculation of weatherization savings is of crucial importance in the selection of the alternative options. Since a strong emphasis was placed on installing only those options which are the most cost effective, accurate estimates of energy savings were required. As a means of achieving accurate estimates of energy consumption, incorporating interactions among weatherization options, and providing a dynamic simulation of the heat transfer process within the dwelling unit, the (BLAST), Building Loads Analysis and Thermodynamics,[2] and (NBSLD), National Bureau of Standards Load Determination[3], computer programs were initially considered. A closer examination of these programs, however, indicated that substantial program modifications would have been necessary in order to use the programs. Consequently, an alternative method of calculating energy savings was developed. These calculations were based on existing methods and modified to incorporate specific considerations such as the use of management devices on window systems (e.g., thermal drapes and shutters).

The calculations used to estimate energy savings associated with a particular option were divided into two major categories: (1) envelope retrofits and (2) mechanical system retrofits. Energy savings for each category are estimated under the assumption that the other category has

---

[1] That is, if the savings from energy conservation are counted, the costs implicit in achieving that level of energy savings must also be counted.

[2] D. C. Hittle, The Building Loads Analysis and Thermodynamics (BLAST) Program Volume I: User's Manual, U.S. Army Construction Engineering Research Laboratory, September 1977.

[3] Tamami Kusuda, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, National Bureau of Standards, Building Science Series 69, July 1976.

already been retrofitted. This ad hoc approach was due to the mutual dependence between the two categories. The analysis was accomplished by holding the level of all options within one category constant while allowing those within the second to vary. One set of calculations were undertaken for each category.[1] Such an approach produces conservative estimates of energy savings for each category.

An illustration of this approach may help to clarify the issue. Suppose we wish to calculate the energy savings associated with the envelope, or architectural, retrofits. Then the level of weatherization which was held fixed in the estimation of energy savings for each architectural option was the efficiency of the mechanical system. The efficiency actually used reflects a mechanical system in good working order. That is, the mechanical system efficiency is consistent with that which would be expected after the mechanical system had been retrofitted.

The energy savings calculations for the architectural options were based on the steady state ASHRAE methods.[2] Savings were calculated on a square foot or linear foot basis. As mentioned above, modifications were incorporated into these calculations to reflect specific considerations. Two types of architectural savings were analyzed, due respectively to reductions in (1) infiltration losses and (2) conduction losses.

Infiltration losses were derived by use of the formula

$$L = 0.24 \cdot Q \cdot \rho \cdot DD \cdot 24$$

where

L = Infiltration heat load;

0.24 = specific heat of air;

Q = cubic feet of air per hour;

ρ = density of air;

DD = degree days; and

24 = hours per day.

---

[1] Under ideal conditions it would be possible to perform more than one set of calculations for each category. However, the scope of this study did not permit multiple levels for both envelope and mechanical system retrofits to be tested.

[2] American Society of Heating Refrigeration and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

In actuality, infiltration losses vary according to which option is used. For example, the cubic feet per hour of infiltration through open holes created by structural cracks, Q, is given by the relationship

$$Q = 300 + 22\left(\frac{DD}{HD}\right)$$

where

DD = degree days; and

HD = heating days.

The ratio DD/HD reflects the average number of degree days per day occurring during the heating season. The cubic feet of infiltration through broken glass or cracks plugged with a rag or some other means is assumed to be one tenth the above figure. Infiltration through cracks around doors and windows is calculated on a linear foot basis by dividing the number of linear feet of doors and windows in an average dwelling unit into 20 percent of the volume of air (in cubic feet) in the conditioned space. For the purposes of this study, the average dwelling unit was assumed to have a volume of 12,000 cubic feet and to contain 344 linear feet of doors and windows.

Conductive losses were derived by multiplying the U-value[1] times the number of degree days. In general, the U-values are based on those presented in the ASHRAE Handbook of Fundamentals.[2] One exception, the U-values for basement walls, is based on work conducted in Twin Rivers, New Jersey, which takes into account the thermal resistance provided by earth fill for wall sections below grade.

For the reader interested in examining the calculations used to estimate energy savings, including those associated with mechanical system retrofits, a more thorough discussion has been prepared and is presented in Appendix B.

Keeping in mind the points discussed above, let us now examine some of the mechanics of calculating life-cycle energy savings and costs. In order to arrive at an adequate dollar value estimate of life-cycle energy savings, we must specify the values of certain key parameters used in the economic analysis. These key parameters are: (1) the severity of the climate; (2) the present cost of energy; (3) the length of the study

---

1 The U-value indicates the number of British thermal units (Btus) which will flow through 1 square foot of envelope section in 1 hour when there is a temperature difference of 1 degree Fahrenheit on opposite sides of the envelope section.

2 American Society of Heating Refrigeration and Air-Conditioning Engineers, ASHRAE Handbook of Fundamentals, New York, 1972.

period; (4) the fuel price escalation rate and (5) the discount rate. Although each of these parameters is discussed in Section 4.2 in some detail, a brief examination of some of their relationships is useful.

The severity of the climate and the present cost of energy are the key parameters needed to determine the first year's annual energy savings. We have seen already that other things being equal, heating energy losses increase linearly as a function of degree days, a measure of the severity of the climate. Suppose we are able to reduce energy losses by X Btu's per square foot per year and our cost per Btu is Y dollars, then our expected annual energy savings is XY dollars per square foot.

In the example presented above we must be careful to identify where the cost per Btu is measured. In general, the cost at the building envelope does not measure the true cost of energy losses to the consumer. This is because the mechanical systems used to heat the residence do not usually operate at 100 percent efficiency. We must therefore develop a measure of energy costs which explicitly includes the efficiency of the mechanical system. To do this we need three additional pieces of information: (1) the cost per unit of fuel; (2) the energy content of that fuel; and (3) the efficiency of the mechanical system. Our measure, equivalent energy cost, shall therefore be taken as the cost per therm (100,000 Btu). That is,

$$\text{cost/therm} = \frac{(100{,}000) \times (\text{cost/unit})}{(\text{Btu content/unit}) \times (\text{Btu output/Btu input})}$$

where Btu output/Btu input is equal to the system efficiency.

In the economic analyses presented in this study, the following Btu contents per unit were used: (1) number two fuel oil, 140,000 Btu per gallon; (2) natural gas, 100,000 Btu per 100 cubic feet; and (3) electricity, 3413 Btu per kilowatt hour. System efficiencies of 65 percent for oil, 70 percent for natural gas, and 100 percent for electricity, were used. For example, in Portland, Maine the cost per gallon of number two fuel oil was 46 cents. This translated into a cost of slightly over 50 cents per therm within the building envelope.

Let us now examine how the length of the study period, the discount rate and the fuel price escalation rate are incorporated. Since each of these factors will be discussed in detail in Section 4.2 the discussion here will focus only on the functional relationship. Suppose expected annual savings are S dollars. We thus want to determine the present value, (i.e. how much) of that annual stream of savings for the given study period. The present value of our total savings over the study period or life-cycle, PVS, are then given by the equation

$$PVS = S \sum_{t=1}^{L} \frac{(1 + P)^t}{(1 + D)^t}$$

where L = the length of the study period;

P = the real rate of fuel price escalation; and

D = the real discount rate.[1]

For ease in calculation all cash flows are assumed to occur at the end of each year. The above equation may then be simplified further by recognizing that

$$\sum_{t=1}^{L} \frac{(1 + P)^t}{(1 + D)^t} = \frac{1 + P}{D - P} \left[1 - \left(\frac{1 + P}{1 + D}\right)^L\right] \text{ if } D \neq P$$

$$= L \qquad \text{if } D = P$$

[1] Real rates are used so that the dollar value of total savings, TS, is expressed in terms of constant purchasing power. In this case, current dollar values have been adjusted to take out the reduction in purchasing power due to inflation.

4.0 ECONOMIC FORECASTS OF OPTIMUM WEATHERIZATION LEVELS

4.1 BASIC ASSUMPTIONS

The general approach used in calculating heating loads and associated energy savings is based on the ASHRAE methodologies presented in the ASHRAE Handbook of Fundamentals.[1] A summary of this approach, including the estimation formulas, is presented in Appendix B.

It is important to note that in this study the ASHRAE calculations are not used to determine the heating load under design conditions for the dwelling unit. Rather, the focus of this study is on estimating the net effect, on the annual heating load, of installing one or more weatherization options. Earlier economic studies have shown that the most important assumption is that "the reduction of Btu losses in any envelope section has a corresponding effect on the reduction of the total heating load."[2]

Implicit in this assumption is that for weatherization categories two through six, reductions in heat losses are independent.[3] That is, energy savings are additive. The first weatherization category, infiltration, however is interdependent with the window and door options, categories two and three. The interdependence issue is of crucial importance because the ASHRAE calculations require the assessment of an option to be independent of the level of any other option. Questions have arisen about the validity of such calculations, but addressing them would require a dynamic simulation. The model therefore treats infiltration first and then assesses the economic viability of the window and door options under the assumption that windows and doors are well fitted.[4] In addition, it is assumed that reducing the heating load requirement does not change the efficiency of associated mechanical systems. The mechanical system efficiencies used in the study are 65 percent for oil, 70 percent for natural gas, and 100 percent for electric resistance heating.[5]

---

[1] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

[2] Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974, p. 22.

[3] The six weatherization categories are: (1) infiltration options; (2) window options; (3) door options; (4) attic insulation; (5) wall insulation; and (6) basement insulation.

[4] That is, infiltration abatement is always assumed to be in place.

[5] The selection of the mechanical systems retrofit options is discussed in a separate report. A brief discussion is provided in Appendix B.

4.2 KEY PARAMETERS USED IN FORECASTS

It was shown in the previous chapter that the choice of the optimal level of investment in a weatherization option depends not only on the installation costs and the annual energy savings attributable to that option, but also on its expected useful life. Since this implies that cash flows will occur throughout the life of the option, a method for comparing these cash flows and those of other options on an equivalent basis is needed. This method incorporates five key factors: (1) a discount rate; (2) a fuel price escalation rate; (3) the useful life of the option; (4) the (present) annual fuel cost savings of the option; and (5) the number of degree days. Changing any or all of these factors can significantly alter the optimal level of investment in a weatherization option. Therefore the values of these key factors that are used in the economic analyses should be carefully selected and based on a sound economic rationale. Let us now examine the economic rationale used in the selection of the representative values for each of these key decision variables.

Discount Rate[1]

A discount rate is that rate of interest which reflects the time value of money. (The "time value" of money stems from the difference between the value of a dollar today and its value at some future time if invested at a stated interest rate.[2] That is to say, a dollar today is worth more than a dollar in ten years, apart from inflation.) The discount rate may therefore be used to bring future costs and savings back to the present so that all options can be compared on an equivalent basis. Second, a real discount rate is one expressed in constant terms (i.e., current dollar values have been adjusted to take out the reduction in purchasing power due to inflation). Therefore, a real discount rate may be thought of as that rate which treats future costs and savings in terms of constant dollars (1977 dollars are assumed in our analysis of optimal weatherization). A 6 percent real rate of interest will be used in this study.[3] Two alternative approaches were used in developing this figure.

---

[1] Most engineering economics texts deal with discount rates and recognize that cash flows occurring in the future must be brought back to some common reference point, e.g., Gerald W. Smith, Engineering Economy: Analysis of Capital Expenditures, 2nd ed., The Iowa State University Press, Ames, Iowa, 1973.

[2] For a detailed discussion of this topic, the interested reader is referred to Rosalie T. Ruegg, et al., Life-Cycle Costing: A Guide for Selecting Energy Conservation Projects for Public Buildings, National Bureau of Standards, Building Science Series 113, September 1978.

[3] Note that this rate is significantly lower than the 10 percent real rate required for Federal Government programs by Circular A-94 of the Office of Management and Budget. It will be shown, however, that for this particular target population a 6 percent real rate is more appropriate.

The first approach assumes that weatherizing low-income housing is a form of income redistribution. In this case, higher income families contribute funds through taxes which are used to finance weatherization activities. As a result of taxation, some higher income families which contribute to the program will have to forego potential investments. That is, there is an opportunity cost associated with the funds contributed through taxation. (The opportunity cost is the return foregone by not undertaking the best investment opportunity available.) Ideally when these funds are redistributed to low-income homeowners in the form of weatherization activities, they should generate a stream of income (benefits or energy savings) equivalent to their best alternative in the private sector. William Baumol asserts that to obtain a social discount rate[1] which is consistent, it should be a "weighted average of the opportunity cost rates for the various sectors from which the project would draw its resources."[2] In essence this doctrine argues that it is the rate of return on capital which is drawn into the government project that should serve for discounting savings and costs.[3] Potential investments which higher income homeowners might have to forego if they "contribute" to weatherization activities are the purchases of short-term government securities or municipal bonds. For example, recent yields on short-term government securities have averaged approximately 10 percent. The effective before tax yield on a 7 percent municipal bond for someone in a 30 percent tax bracket would also be 10 percent.[4] Assuming a long term (20 to 25 year average) rate of inflation of 4 percent produces a real discount rate of 6 percent.

---

[1] A social discount rate is one which is appropriate for society as a whole rather than for a particular individual.

[2] William Baumol, "On the Discount Rate for Public Projects," Analysis and Evaluation of Public Expenditures: The PPB System, Joint Economic Committee, U.S. Government Printing Office, Washington, D.C., 1969.

[3] The economic principles behind this claim are discussed in detail in Walter Nicholson, Microeconomic Theory: Basic Principles and Extensions, The Dryden Press, Inc., Hinsdale, Ill., 1972.

[4] In the case of a tax free bond, the effective yield, EY, is given as

$$EY = Y/(1-TR)$$

where Y = yield quoted on the face of the bond; and
TR = the tax rate of the holder of the bond.

In the example given above, EY is given as

$$EY = 0.10 = (0.07)/(1.00-0.30).$$

Note that the effective yield, EY, is higher than the yield quoted on the face of the bond. This results from the assumption that the bond was tax free.

Theoretically the opportunity cost is a measure of the "best" alternative foregone. In reality higher income consumers can probably undertake investments which have before tax yields in excess of 10 percent. Investments in housing (for personal use) are an excellent example. Figures from the Final Report of the Task Force on Housing Costs can be used to illustrate this point.[1] During the 1972 to 1976 period, the median sales price of new single family homes rose at an annual rate of 12.5 percent. During the same period, the median sales price of existing single family homes rose 9.3 percent. Projections for the increase in the median sales price for all single family homes over the next 10 years are approximately 10 percent. These figures represent lower bound estimates on the rate of return on a housing investment, however, since the return is computed with respect to the owner's equity rather than the full purchase price of the house. Transaction costs are high, however, usually averaging 6 percent for realty fees. Points may also be charged for certain types of financing. Although these factors tend to reduce the rate of return on the housing investment, it appears quite likely that the rate of return on the investment would exceed 10 percent. This is an indication that a real social discount rate of 6 percent is a lower bound estimate. The inclusion of funds from private industry would tend to increase the real discount rate toward the 10 percent figure required by the Office of Management and Budget.

The second approach is based on the assumption that low-income families are primarily borrowers. Consequently, their opportunity cost is a measure of the costs of transferring consumption from the present to the future through borrowing. The lending rates they face thus represent the rate at which they can trade present consumption for future consumption. (See Appendix C.1 for a theoretical treatment of this topic.) It is important to point out that an individual may face more than one lending rate. For example, the physical process of weatherization may be interpreted as housing renovation. Thus the lending rate faced by the individual is the one for home improvement loans. Note that lending rates for home improvements tend to be somewhat lower than those for other goods and sevices (for example, revolving charge accounts). If we take a representative rate for home improvement/renovation loans, a discount rate of 7 to 12 percent[2] results. The term on these loans is usually between 10 and 12 years. Therefore, the savings generated by the weatherization activities should be sufficient to permit the low-income homeowner to pay back the loan within a 10 to 12 year period. In order to get a real

---

[1] U.S. Department of Housing and Urban Development, Final Report of the Task Force on Housing Costs, May 1978.

[2] Note that when the wider spectrum of renovation and rehabilitation programs is considered, it is possible for low and moderate income families to obtain loans at rates substantially below the market rate of interest. See David Gressel, Financing Techniques for Local Rehabilitation Programs, National Association of Housing and Redevelopment Officials, Washington, D.C., 1976.

discount rate from this figure it is necessary to adjust for the anticipated long term (20 to 25 year average) rate of inflation. Assuming a long term rate of inflation of 4 percent produces a real discount rate of approximately 3 to 8 percent.

In our initial investigations, figures between 3 and 10 percent were used. (See the sensitivity analysis presented in Section 4.2.2.) However, since a nationwide weatherization loan program will probably offer lower interest rates, our emphasis has focused on using an intermediate estimate of 6 percent. This should provide us with a means of insuring a high degree of comparability between the field experiences of the demonstration program and the anticipated market responses of any future loan programs.

Fuel Price Escalation Rate

As was indicated earlier, the future energy savings (cash flows) associated with alternative weatherization options must be brought back to the present (or recovered) so that they can be compared on an equivalent basis. Therefore, in addition to a discount rate, an estimate for the long range rate of fuel price escalation is needed. Its choice is subject to somewhat more uncertainty than choosing an appropriate discount rate, for several reasons. First, fuel prices may be rigidly established by the Federal government. This is usually done to correct market imperfections. The impact of such a policy however may be contrary to that desired.[1] Furthermore, energy prices may be strongly affected or even imposed by a cartel, such as OPEC. Usually a cartel operates so that the cartel members maximize their joint profits. Such activities are, generally speaking, impossible to forecast so that any estimate affected by the behavior of cartels is fraught with uncertainity. Thus it is not surprising that estimates of the long term rates of fuel price escalation are extremely variable. Ranges of real rates between 0 (constant energy costs) and 12 (more than tripling every 10 years) percent have been used in recent economic studies. Although ranges might be useful to see how sensitive a weatherization option is to rising fuel prices, they do not provide us with enough precision to make reliable tradeoffs. To do this a specific estimate within the range is needed.

---

[1] Shortages are likely to result with price regulation because a greater quantity will be demanded than producers are willing to supply. This may cause non-renewable resources to be wasted and finally result in either rationing or deregulation. One way in which this problem can be treated when dealing with energy conservation is through the use of resource impact factors (RIF^{s}). Current research efforts in this area are presented in Stephen F. Weber, The Effect of "Resource Impact Factors" on Energy Conservation Standards for Buildings, National Bureau of Standards, Building Science Series 114, September 1978.

Note that there are econometric methods which can be used to produce estimates which are "statistically desirable." All of these methods, however, involve data bases and complicated computer programs which should, at least in theory, be examined to determine the adequacy of the raw data and the merits of the estimate. Several Federal Agencies, which own and operate buildings, have reliable empirical data for the various regions of the country for which econometric forecasts have been made. Furthermore, these Federal agencies have an incentive to make reliable estimates since they are required to perform economic analyses of potential energy conserving options prior to construction or renovation. The Department of Defense is one Federal agency which has made public the forecasts it uses for long term real rates of fuel price escalation. These rates are summarized in Table 4.1.

TABLE 4.1 ESTIMATED REAL RATES OF FUEL PRICE ESCALATION USED IN ECONOMIC ANALYSES

Fuel	Rate
Oil	8%
Coal	5%
Natural Gas	8%
LPG	8%
Electricity	
New England	7%
Pacific	7%
All others	6%

Source: Assistant Secretary of Defense (Installations and Logistics) Memorandum, Energy Conservation Investment Program Guidance, March 24, 1977.

Estimates of short term rates for fuel price escalation are also available through the Department of Defense. In some instances these rates are given on a regional basis. Telephone conversations with local GSA and utility representatives have indicated that the short term rates forecast by the Department of Defense were comparable to recent increases in fuel prices. Table 4.2 summarizes these rates. If these forecasts are accepted on the basis of past performance, then more confidence can be placed in the long term rates reported in Table 4.1.

TABLE 4.2 ESTIMATED SHORT TERM RATES OF FUEL PRICE ESCALATION (1 October 1977 to 30 September 1980)

Fuel	Rate
Coal	10%
Oil	16%
Natural Gas	16%
LPG	16%
Electricity	16%

Source: Assistant Secretary of Defense (Installations and Logistics) Memorandum, Energy Conservation Investment Program Guidance, March 24, 1977.

The rates used in the economic analyses presented in this study are those presented in Table 4.1.

The Useful Life of the Option

In an earlier example it was noted that not all options have the same useful life. The introduction of option life as a variable poses several problems when choosing among mutually exclusive weatherization investment alternatives. Even in the case when two or more alternatives can be installed together as a unit, varying lives can cause analytical problems. Thus in order to provide a rational means for choosing among weatherization options a life cycle, or study period, must be selected. The choice of the life cycle is significant since a lengthy study period would tend to favor options with a long life whereas a short one would significantly reduce the set of feasible options.

In selecting a representative life cycle both economic and engineering concepts were taken into consideration. This analysis indicated that a suitable study period would be 20 years. From an economic viewpoint, 20 years is about as far into the future as values for key factors, such as the discount rate and the fuel price escalation rate, can be projected without introducing either unacceptable uncertainties or unrealistic assumptions. From an engineering viewpoint, 20 years provides a conservative estimate of the useful life of most of the options without biasing

the selection toward those options which will likely last as long as the building. For these reasons the 20 year study period has been used in other economic analyses of residential weatherization.[1]

Using a study period of 20 years, we must now determine the life-cycle costs of each option. In order to estimate life-cycle costs, assumptions about the relative durability of the alternative weatherization options must be made. These assumptions, based on engineering experience, are summarized in Table 4.3. The cost of the option over the life cycle may now be estimated. The present value option's of the cost is equal to the initial cost (i.e., the installation cost) plus any future costs (discounted to a present value) resulting from required maintenance, repair or replacement. The estimate uses a 20 year life cycle and a six percent real discount rate; a zero real price increase in the cost of the option is used in the calculation. The present value (life-cycle) cost of an option, PVC, may now be expressed mathematically as

$$PVC = C_o + \sum_{t=1}^{20} \frac{C_t}{(1.06)^t}$$

where

C_o = the installation cost, and

C_t = the costs for maintenance, repair, or replacement occurring in year t (C_t may be equal to zero).

Life-cycle cost estimates for each option and each demonstration site are given in Appendix A of this report.

Annual Fuel Cost Savings

Annual fuel cost savings are determined by the estimated annual reductions in energy consumption and the cost per unit of energy. More precisely, the annual fuel cost savings, AS, are given by

$$AS_{ij} = \Delta Q_i \cdot P_j$$

where i identifies the option, j denotes the fuel type, ΔQ is the quantity changein consumption (Btu) for the i^{th} option and P_j is the price per energy unit of the j^{th} fuel type. Since methods for calculating physical energy

[1] Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

TABLE 4.3

ESTIMATES OF THE FREQUENCY OF REPLACEMENT OF BUILDING MATERIALS TO ACHIEVE A 20 YEAR PHYSICAL LIFE

OPTIONS NOT HAVING 20-YEAR PHYSICAL LIFE	REPLACEMENT ESTIMATE[a]
Replace broken glass	Replace 2.5% of glass area at end of 10 year.
Reset glazing	Replace 10% of glazing at end of 10th year.
Low emissivity film	Replace 100% of film at end of years 9 and 18.
Weatherstrip windows	Replace 25% of weatherstripping at end of 10th year.
Caulk windows	Replace 25% of caulking at end of years 8 and 16.
Insulating drapes	Replace 100% of drapes at end of year 10.
Storm door	Replace 25% of door cost at end of year 10.
Weatherstrip door	Replace 25% of weatherstripping at end years 5, 10, and 15.
Caulk doors	Replace 50% of the caulking at the end of the 10th year.
Replace threshold	Replace 100% of the thresholds at the end of the 10th year.
Attic insulation	Replace 25% of the blown-in insulation at end of 15th year.
Weatherstrip attic hatch	Replace 100% at end of 15th year.
Carpet floor	Replace 100% at end of years 7 and 14.

[a] McClure Godette, Installation of Architectural Options, National Bureau of Standards, Interagency Report, (in press).

savings[1] were discussed in Section 3.2, we shall focus our attention on how the figures for the cost per unit of energy were derived.

The first requirement for energy savings to be representative is that the rates used for each fuel type reflect local supply and demand factors in the region under study and be as up-to-date as possible. In order to ensure that these considerations were met, CSA representatives in each of the demonstration sites were contacted. In some cases, this field survey produced the desired level of reliability in that the representatives were able to quote recent prices. In other cases, the local representatives were unable to provide up-to-date information on energy prices. The names and phone numbers of local suppliers of the different types of fuel were then requested, and suppliers were contacted directly to obtain the necessary information.

It is important to point out here several elements incorporated in the energy prices used for our economic analyses. These price considerations included local taxes and surcharges and the existence of block rates. Block rates are important in that they depend on the amount of fuel consumed and are used for natural gas and electricity in almost all demonstration cities. Several cases where neither the CSA contact nor the local supplier could provide an estimate of the average price per unit of fuel or the average amount of fuel used per year, a price estimate based on an average annual heating requirement of 90 million Btu's was used.[2] A final check was made with the prices quoted in the Bureau of Labor Statistics' December 1977 issue of Retail Prices and Indexes of Fuels and Utilities: Residential Usage.[3]

Number of Degree Days[4]

As indicated in Section 2.1, the demonstration sites were selected primarily on the basis of climate factors. The sites were chosen so as to represent all the important inhabited climates of the country. In

---

[1] Note that the number of Btu's saved (physical energy savings) depends on of the number of degree days. We shall explore some of the implications of this relationship to dollar energy savings in the topic which follows.

[2] 75,000 Btu's per square foot per year times 1200 square feet.

[3] Retail Prices and Indexes of Fuels and Utilities: Residential Usage, Department of Labor, Bureau of Labor Statistics, December 1977.

[4] Degree days are based on 65°F rather than 70°F as the 5°F temperature differential is considered to be provided by small solar radiation gains and internal heat sources rather than direct heating and should therefore not be reflected in direct energy savings. For this reason all energy savings calculations, while reflecting a 70°F inside temperature, are based on 65°F.

terms of base heating loads as measured by the annual number of degree days, the demonstration sites range from 206 to 9271. Such a wide variation is particularly useful from an economic viewpoint since previous studies have shown that doubling the number of degree days is equivalent to doubling the cost of energy.[1] (This relationship can be seen by referring to Appendix B where the calculations used to estimate energy savings are presented. Both degree days and the cost of energy enter multiplicatively into the calculation which determines annual energy savings.) Degree days therefore not only represent a key factor in weatherization investment decisions but also provide a means for, other things being equal, generalizing the results of the demonstration program.

4.3 CASE STUDY: PORTLAND, MAINE

In order to highlight the economic issues discussed in Chapter 3, an indepth analysis of the forecast optimum weatherization package for Portland, Maine is presented in this section. This analysis is divided into two parts. In the first part, an optimum weatherization package is given based on a balance point[2] of 65°F and a specific set of values for the key decision factors discussed in Section 4.2 is given. This case is regarded as the baseline forecast since the values used are the ones which are most likely to prevail in the Portland, Maine area. In the second part, a sensitivity analysis is performed to determine how "sensitive" the optimal weatherization package is to changes in the value of one or more of the key parameters. This type of analysis is particularly useful because it permits the impacts of changing assumptions[3] or forecast errors[4] to be quantified.

4.3.1 Baseline Forecasts

The purpose of this section is to present in detail the results of the baseline forecast for Portland, Maine. The term baseline is used because the assumptions and the values of the key decision variables are the ones which are most likely to prevail in the Portland area. Table 4.4 summarizes the assumptions and values of the key decision variables used in the analysis.

---

[1] Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

[2] The balance point is defined as the average outside temperature at which the heating system comes on to maintain the interior thermostat setting.

[3] For example, changing the discount rate from 6 percent to 3 percent to reflect of an assumed interest subsidy.

[4] Forecast errors are likely in most estimates of the rate of future fuel price escalation. Breaking the estimate up into short and long term rates which will most likely bracket the true value can somewhat reduce the chance of incorrect decisions.

Several of the factors mentioned in Table 4.4 are expected to vary across demonstration sites. Although this variation does imply that different sites will have different baselines, the use of a constant base temperature of 65°F should somewhat simplify comparisons among sites and facilitate the generalization of results.

Two additional factors not covered in Table 4.4 are the type of construction and cost of the option. Both of these factors are expected to vary across sites as a function of tastes and trends in the demand for housing and of changing conditions in the markets for local construction, labor and building materials.

Prior to participation in the demonstration program, each candidate site was asked to submit from 27 to 50 homes which satisfied an extensive set of criteria outlined in the CSA Weatherization Demonstration Project Plan.[1] A wood frame construction type is used in the baseline forecast. This is because the vast majority of the homes submitted by the local CSA agency at Portland were of that type. In making the baseline forecast a prototypical design for a wood frame house was specified. Based on information submitted by the local CSA agency, the house used in making the baseline forecast is a one story rectangular box measuring 30 feet by 40 feet with a full basement. (An average basement temperature of 44°F during the heating season is used in the forecast.) The house contains 240 square feet of glazed area with an average window size of 15 square feet.

TABLE 4.4 VALUES OF KEY DECISION VARIABLES USED IN THE BASELINE FORECAST: PORTLAND, MAINE

Number of Degree Days	7493
Discount Rate	6%
Type of Fuel	Fuel Oil
Fuel Price Escalation Rate	8%
Length of Study Period	20 years
House Construction Type	Wood Frame - 1 Story Detached
Floor Area	40 ft x 30 ft
Foundation Type	Full Basement

[1] Richard Crenshaw, Roy Clark, Robert Chapman, Richard Grot and McClure Godette, CSA Weatherization Demonstration Project Plan, National Bureau of Standards, NBSIR 79-1706, March 1979.

Based on this information and the specifications established in Appendix A.2, local CSA agency representatives were contacted and requested to provide data on the costs of installing each of the weatherization options. Each of these cost estimates reflects the locally preferred choice between installation by the local community action group or by a local building contractor.

The information on costs (see Appendix A.3) and the number of degree days (see Appendix B.2) was then read into a computer time-sharing system and stored in a user file. (Each demonstration site had its own user file.) All forecasts were made through an application of the computer program, Community Services Administration Optimum Weatherization Package (CSAOWP), described in Appendix D.

The output of the computer program consists of a brief summary of data inputs and six sets of weatherization option outputs. The six sets are: (1) infiltration options, (2) window options, (3) attic insulation, (4) door options, (5) wall insulation above grade, and (6) basement wall. The first portion of the output which corresponds to the baseline forecast for Portland, Maine is shown below as Exhibit 4.1.

Exhibit 4.1 Computer Output: Input Summary and Infiltration Options

PORTLAND MAINE 7505 DEGREE DAYS

CALCULATIONS FOR A FRAME DETACHED HOUSE WITH FUEL TYPE: FUEL OIL

FUEL PRICE ESCALATION RATE = .08 DISCOUNT RATE = .06
LIFETIME OF OPTIONS = 20 $/UNIT OF FUEL = $ 0.46

INFILTRATION OPTIONS

OPTION	20PVS	20PVC	S/C	11PVS	11PVC
REPLACE BROKEN GLASS	230.14	6.39	36.03	115.90	6.39
RESET GLAZING	2.79	0.41	6.78	1.41	0.41
REPLACE THRESHOLD	338.23	9.35	36.17	170.32	9.35
SEAL STRUCT'L CRACKS	338.23	0.80	422.78	170.32	0.80
WEATHSTP WINDOWS	2.79	0.46	6.13	1.41	0.46
CAULK WINDOWS	2.79	0.38	7.42	1.41	0.35
WEATHSTP DOORS	2.79	0.57	4.88	1.41	0.53
CAULK DOORS	2.79	0.38	7.28	1.41	0.38
WEATHSTP ATTIC HATCH	2.79	0.57	4.93	1.41	0.40

Notice that each of the nine infiltration options has five columns associated with it. All entires in these columns are in dollar terms. These five columns show: (1) the present value of energy savings over the 20 year life cycle, 20 PVC, (2) the present value

of option costs (including replacements) over the 20 year life cycle, 20 PVC, (3) the 20 year savings-to-cost ratio, S/C, (4) the present value of energy savings in the first 11 years, 11 PVS, and (5) the present value of option costs in the first 11 years, 11 PVC. Recall that a payback constraint of 11 years has been placed on each architectural option; if the figure printed in the 11 PVS column is greater than the figure in the 11 PVC column, we can assert that the option satisfies this constraint. Note that all nine of the infiltration options are included in the optimum weatherization package since their savings-to-cost ratio is greater than (or equal to) 1 and they all satisfy the 11 year payback constraint.

The second set of calculations is concerned with window options. The output from the base line forecast for this set is shown below as Exhibit 4.2.

Exhibit 4.2 Computer Output: Window Options

WINDOW OPTIONS

BASE ENERGY COST = 25.1304

OPTION	20PVS	20PVC	*20PVS	*20PVC	S/C	11PVS	11PVC
STAGE 1							
STORM WINDOW	12.68	2.40	12.68	2.40	5.28	6.38	2.40
INSUL. DRAPE	4.12	2.34	4.12	2.34	1.76	2.07	2.34
INSUL. SHUTTER	12.47	3.50	12.47	3.50	3.56	6.28	3.50
LOW EMISIV. FILM	8.67	3.30	8.67	3.30	2.63	4.37	2.71
STAGE 2							
STORM + DRAPE	13.67	4.74	1.00	2.34	0.43	6.89	4.74
STORM + SHUTTER	18.16	5.90	5.49	3.50	1.57	9.15	5.90
STORM + FILM	16.168	5.70	4.00	3.30	1.21	8.40	5.11
TRIPLE	17.12	4.80	4.45	2.40	1.85	8.62	4.80
STAGE 3							
TRIPLE + DRAPE	17.62	7.14	0.50	2.34	0.21	8.87	7.14
TRIPLE + SHUTTER	20.37	8.30	3.24	3.50	0.93	10.26	8.30
TRIPLE + FILM	18.90	8.10	1.78	3.30	0.54	9.52	7.51

Notice that in the upper left hand corner a base energy cost figure is given. This figure states that over the 20 year life cycle slightly over $25 worth of energy (in present value terms) is lost through each square foot of single-glazed window. From the output it can be seen that three stages of analysis are performed in selecting the optimal combination of window options. Each stage corresponds to an incremental analysis which uses the results of the previous stage, or base, an input. For example, in Stage 1 we wish to identify the most cost-effective option whichhcan

be applied to the existing single-glazed window. Consequently, we must refer to the information contained in each of the seven columns in the output. The same meaning as in the previous analysis (for infiltration options) is associated with each of the following column headings: 20 PVS, 20PVC, 11 PVS, and 11 PVC. Two new columns have now been added and the S/C column has been redefined. These columns, *20PVS and *20PVC, are the incremental savings and incremental costs over the 20 year life cycle associated with each option.[1] The S/C column has been redefined such that S/C is equal to *20PVS divided by *20PVC rather than 20PVS/20PVC. Notice that in Stage 1, because we are comparing savings and costs for each of the options to the single-glazed window, 20 PVS is equal to *20PVS and 20 PVC is equal to *20PVC.[2] From the Portland baseline output it can easily be seen that a storm window is the most cost-effective option to install in the first stage. Consequently the storm window is used as an input (i.e., it is the new base) in calculating weatherization savings and costs in the Stage 2 analysis. A close examination of the Stage 2 output reveals that 20 PVS is greater than 20 PVC for all four possibilities. The addition of a thermal shutter or a low-emissivity film, although it may produce total savings which exceed total costs, may not be cost effective because it does not increase <u>net</u> savings to the homeowner. For this reason we must examine the incremental savings and costs given by the entries in the *20PVS, *20PVC and S/C columns. Such an examination shows that the installation of triple glazing, accomplished through the addition of another storm window, is the most cost-effective option. Stage 3 then proceeds on the assumption that the window system is triple glazed. In Stage 3 weatherization savings and costs are calculated for three possibilities: the addition of a thermal drape, a thermal shutter, and a low-emissivity film. From the entries in the *20 PVS, *20PVC and S/C columns it can be seen that none of these options will increase net savings to the homeowner. We can thus assert that triple glazing corresponds to the optimal glazing system for the Portland, Maine baseline case.

The question of the economic implications of a payback constraint were alluded to earlier. In Appendix C it will be shown that basing investment decisions solely on a payback criterion would not be economically efficient. The third stage of the window analysis serves to highlight this point. All of the Stage 3 options clearly satisfy an 11 year payback criterion. However, if a decision to install both triple glazing <u>and</u> a low-emissivity film were made based on the figures in the 11 PVS and 11 PVC columns, the homeowner's net savings would actually be <u>reduced</u> by almost <u>$23 per window</u> over the 20 year life cycle.[3]

---

[1] Here "incremental" is defined relative to the base energy cost or the previous stage.

[2] That is, marginal savings is total savings and marginal cost is equal to total cost for the <u>first</u> unit.

[3] The $23 figure is based on an average window size of 15 square feet.

The third set of calculations is concerned with attic insulation. The output from the baseline forecast for this set of calculations is shown below as Exhibit 4.3.

Exhibit 4.3 Computer Output: Attic Insulation

ATTIC INSULATION

BASE ENERGY COST = 4.22546

OPTION	20PVS	20PVC	*20PVS	*20PVC	S/C	11PVS	11PVC
R-11 INSUL.	2.78	0.19	2.78	0.19	14.81	1.40	0.17
R-19 INSUL.	3.25	0.33	0.47	0.14	3.25	1.64	0.30
R-30 INSUL.	3.54	0.47	0.29	0.14	2.01	1.78	0.43
R-38 INSUL.	3.67	0.62	0.13	0.15	0.87	1.85	0.56

As in the previous set of calculations, a base energy cost figure is given in the upper left hand corner of the output. This figure indicates that conductive heat losses are approximately $4.25 per square foot for the attic over the 20 year life cycle. An examination of the output on attic insulation reveals that the incremental savings-to-cost ratio is declining, but remains greater than unity for all levels of resistance up to R-30. This implies that all increases in the level of attic insulation up to R-30 would result in increased net savings to the homeowner. At R-38 however, the incremental savings-to-cost ratio is less than 1. Thus increasing the level of attic insulation from R-30 to R-38 would not increase the homeowner's net savings.

The last sets of calculations are concerned with wall insulation (frame and basement) and door options. The outputs from the baseline forecast for these three sets of calculations are shown below as Exhibit 4.4.

Exhibit 4.4 Computer Output: Wall Insulation Above Grade, Basement Wall, and Door Options

WALL INSULATION ABOVE GRADE[1]

BASE ENERGY COST = 4.89264

OPTION	20PVS	20PVC	S/C	11PVS	11PVC
R-11 INSUL.	3.36	0.80	4.20	1.69	0.80

[1] The term "grade" refers to the ground level at the outside walls of the building.

BASEMENT WALL

OPTION	20PVS	20PVC	S/C	11PVS	11PVC
BASE ENERGY COST = 8.44565					
R-7 ABOVE GRADE	7.14	0.70	10.19	3.59	0.70
BASE ENERGY COST = 2.16555					
R-7 BELOW GR. 2 FT.	1.27	0.70	1.81	0.64	0.70
BASE ENERGY COST = 1.54837					
R-7 BELOW GR. 4 FT.	0.77	0.70	1.11	0.39	0.70
BASE ENERGY COST = 1.23436					
R-7 BELOW GR. 6 FT.	0.55	0.70	0.78	0.28	0.70

DOOR OPTIONS

OPTION	20 PVS	20PVC	S/C	11PVS	11PVC
BASE ENERGY COST (0% GLASS) = 10.1652					
STORM DOOR	3.27	4.56	0.72	1.65	4.56
SECOND WOOD DOOR	5.72	5.20	1.10	2.88	5.20
NEW INSUL. DOOR	6.38	5.70	1.12	3.22	5.70
BASE ENERGY COST (10% GLASS) = 11.6599					
STORM DOOR	4.77	4.56	1.05	2.40	4.56
SECOND WOOD DOOR	7.21	5.20	1.39	3.63	5.20
NEW INSUL. DOOR	7.88	5.70	1.38	3.97	5.70
BASE ENERGY COST (30% GLASS) = 14.6538					
STORM DOOR	7.76	4.56	1.70	3.91	4.56
SECOND WOOD DOOR	10.21	5.20	1.96	5.14	5.20
NEW INSUL. DOOR	10.87	5.70	1.91	5.48	5.70
BASE ENERGY COST (60% GLASS) = 19.1434					
STORM DOOR	12.25	4.56	2.69	6.17	4.56
SECOND WOOD DOOR	14.70	5.20	2.83	7.40	5.20

As in the previous sets of calculations, base energy cost figures are given in the upper left hand corner of each output. Notice that four separate sets of base energy costs are given for the basement wall calculations and for the door options. Separate calculations are needed for basement walls to allow for the resistance to heat flows caused by the varying amounts of earth fill surrounding the basement wall. Separate base energy calculations are needed for the exterior door to allow for the effects of varying amounts of glass in the door. These calculations are particularly important because the U-value of the exterior door increases as the glass area increases. Referring to the output it can be seen that the base energy costs over the 20 year life cycle increase from slightly over $10 per square foot to slightly over $19 per square foot as the glass area increases from zero to 60 percent.

In the first set of calculations the cost-effectiveness of installing R-11 insulation in the wall cavity is assessed. No other values of wall cavity insulation were analyzed since most frame construction uses two by four studding. From the calculations above we can see that installing R-11 insulation in the wall cavity is quite cost-effective. The 11 year payback criterion is also satisfied.

The second set of calculations assesses the cost-effectiveness of R-7 insulation applied directly to the basement wall. (Note that in this case 11PVC is equal to 20PVC. This phenomena stems from the fact that no future replacements are needed to attain a 20 year life.) From the changing base energy costs, it can be seen that potential savings are reduced as we move to depths further below grade. (This is due to the increased thickness of the earth fill.) The energy savings calculations for the basement wall are thus designed to answer two questions: (1) should we insulate above grade and (2) if so, how far below grade should we insulate. The output indicates that it is cost-effective to insulate as far as four feet below grade. Unfortunately, when we examine the 11 year savings and costs we find that the 11 year payback criterion is not satisfied for the option if it is applied to a depth of two or more feet below grade. Consequently, basement wall insulation will only be applied to those sections which are above grade. (Not insulating to four feet below grade will somewhat reduce the net savings to the homeowner over the 20 year life cycle.)

In the third set of calculations, we wish to examine three potential door retrofits: the installation of an aluminum storm door, the installation of a second wood door, and removing the existing door and replacing it with an insulating door. It is interesting to note that the installation of a storm door is found to be less cost-effective than either of the other two options. In fact, in the case where the exterior door contains no glass the present value of the energy savings (20 PVS) is less than the cost of the storm door to the homeowner (20 PVC). A close examination of the computer output reveals that a second wood door is slightly more cost-effective than an insulating door if the amount of glass in the door is greater than or equal to 10 percent. In the first two cases (0% glass and 10% glass) we see that the imposition of a pay-

installation of a second wood door, 11 PVS differs from 11 PVC by only six cents. (Since this is less than two percent of the total cost figure, we can assume that the payback criterion is satisfied.) In the fourth case the 11 year payback criterion is easily satisfied. Thus for the Portland, Maine baseline the installation of a second wood door is recommended whenever the glass area in the exterior door is 30 percent or more.

4.3.2 Sensitivity Analysis

A sensitivity analysis was performed in order to get a better understanding of the factors affecting the selection of the optimum weatherization package. The sensitivity analysis makes use of the computer program discussed in Appendix D. Four specific variables were studied. They were: (1) average installation costs, (2) balance point, (3) fuel price escalation rate (both short and long term rate changes were considered), and (4) discount rate. Three values were chosen for each of these variables; including all combinations, this resulted in 81 different cases. These variables were shown to have a definite effect on the options selected in the optimum weatherization package.

In addition to these variable factors, there were other assumed conditions for the analysis. These assumed conditions were held the same as in the baseline forecast. They include a frame house type, fuel oil as the major heating source, a fuel price of $0.46 per gallon, and a study period of 20 years.

The values for installation costs of the options were based on estimates obtained from Portland field representatives. All costs were adjusted where needed to obtain an estimate of the costs of that option over the 20 year life cycle. (These are the same costs which were used in the selection of the optimum weatherization package discussed in Section 4.3.1.) In order to look at the effect of variations in costs on the options selected, values that were 20 percent higher than the original estimates and 30 percent lower were used. These two sets of values were chosen to cover those cases where either substantial amounts of preparation work are needed or where labor or materials can be obtained at a discount.

Three balance points were considered. They were 55°F, 65°F and 70°F. As indicated earlier, predicting the rates of future fuel price escalation is very sensitive to a particular set of assumptions[1] and consequently may be highly volatile. Thus the rate of fuel price escalation is of fundamental importance in any sensitivity analysis. The baseline value used was the 8 percent real rate[2] recently forecast by the Department of Defense for fuel oil. In addition to that value, a short and long term

---

[1] For example, the assumed behavior of the OPEC members might change.

[2] Assistant Secretary of Defense (Installations and Logistics) Memorandum, Energy Conservation Investment Program Guidance, March 24, 1977.

escalation rate combination of 0 percent for the first four years and 10 percent thereafter was used. This approach permits us to examine the effect of short term stable fuel prices and high future rates on the selection of the optimal weatherization package. The other extreme, rapidly increasing fuel prices over the short term and modest increases in the long term, was modeled by using a rate combination of 12 percent for the first four years and 4 percent for the remainder of the 20 year life cycle.

The last key parameter in the analysis was the discount rate. In addition to the baseline rate of 6 percent, rates of 3 and 10 percent were used. (All rates quoted are real rates.) The 10 percent rate was chosen because it is consistent with the rate mandated in OMB circular A94. This permits us to determine the optimal level of weatherization if low-income homeowners are forced to compete against other government energy conservation projects for funds.[1] The 3 percent rate was chosen to cover the case where the Federal government provides an interest subsidy to the low-income homeowner as an integral part of the weatherization loan.

From the previous discussion, it can be seen that some conditions are held constant throughout the sensitivity analysis whereas others are allowed to vary both singly and in combination. To promote a clearer understanding of the sensitivity analysis, both sets of conditions are summarized in Table 4.5.

To facilitate the presentation of the results of the 81 cases examined in the sensitivity analysis, a reference table has been prepared. The purpose of this table is to identify what options are included in each of the 12 weatherization packages which emerged from the sensitivity analysis. Referring now to Table 4.6, we can see that the most basic (i.e., least cost or lowest level of weatherization) weatherization package, denoted as "A", consists of all nine infiltration options, storm windows, R-19 insulation in the attic, and R-7 insulation on all basement walls above grade. In all cases infiltration abatement tends to be particularly cost effective due to the relatively high air change rates observed in the low-income homes participating in the Portland demonstration. Referring once again to Table 4.6 we see that weatherization package "B" is the same as "A" with the exception that installing insulation (R-11) in the wall cavity is now cost effective. Weatherization package "C" indicates that in addition to those options identified in "B", R-30 insulation in the attic is now cost effective. Triple glazing first becomes cost effective with weatherization package "D". It is important to point out that weatherization package "D" forms a basis for all of the remaining weatherization packages. For example, weatherization package "E" includes R-7 insulation on all basement walls to a depth of two feet below grade, whereas weatherization package "F",

---

[1] For example, Federal grants to retrofit schools and other public buildings require that a real discount rate of 10 percent be used.

TABLE 4.5 OVERVIEW OF FACTORS TREATED IN THE SENSITIVITY ANALYSIS

CONSTANT CONDITIONS

° Frame House

° Fuel Oil

° Initial Fuel Price: $0.46 per gallon

° 20 Year Study Period

VARIABLE CONDITIONS

° Average Installation Costs

- Current Costs (Baseline)
- Current Costs + 20%
- Current Costs - 30%

° Balance Point

- 55°F
- 65°F (Baseline)
- 70°F

° Fuel Price Escalation Rate

- 8% (Baseline)
- 0% Short and 10% Long
- 12% Short and 4% Long

° Discount Rate

- 3%
- 6% (Baseline)
- 10%

TABLE 4.6 OPTIMAL WEATHERIZATION PACKAGES DETERMINED FROM THE SENSITIVITY ANALYSIS

A

All Infiltration
Storm Windows
R-19 Attic
R-7 Basement-Above grade

B

All Infiltration
Storm Windows
R-19 Attic
R-7 Basement-Above grade
R-11 Wall

C

All Infiltration
Storm Windows
R-30 Attic
R-7 Basement - Above grade
R-11 Wall

D

All Infiltration
Triple Glazing
R-30 Attic
R-7 Basement - Above grade
R-11 Wall

E

All Infiltration
Triple Glazing
R-30 Attic
R-7 Basement - Above grade
R-11 Wall
R-7 Basement 2 feet below grade

F = BASELINE

All Infiltration
Triple Glazing
R-30 Attic
R-7 Basement - Above grade
R-11 Wall
2nd Wood Door (30% glass)

G

All Infiltration
Triple Glazing + Shutter
R-38 Attic
R-7 Basement-Above grade
R-11 Wall

H

All Infiltration
Triple Glazing + Shutter
R-30 Attic
R-7 Basement Above grade
R-11 Wall
R-7 Basement - 2 feet below grade

I

All Infiltration
Triple Glazing
R-30 Attic
R-7 Basement - 2 feet below grade
2nd Wood Door (30% glass)

J

All Infiltration
Triple Glazing + Shutter
R-38 Attic
R-7 Basement - Above grade
R-11 Wall
2nd Wood Door (30% glass)

K

All Infiltration
Triple Glazing + Shutter
R-38 Attic
R-7 Basement - Above grade
R-11 Wall
R-7 Basement - 2 feet below grade
2nd Wood Door (30% glass)

L

All Infiltration
Triple Glazing + Shutter
R-38 Attic
R-7 Basement - Above grade
R-11 Wall
R-7 Basement - 2 feet below grade
2nd Wood Door (10% glass)

the baseline package, does not. Weatherization package "F" does however include all options listed under "D" plus the use of a second wood door on exterior doors in which glass area is 30 percent or more. The six remaining packages usually consist of two or more additions to weatherization package "D". For example, "G" adds the use of a thermal shutter and R-38 insulation in the attic to "D". The largest weatherization package, "L", adds to "D" the use of a thermal shutter, R-38 insulation in the attic, R-7 insulation on all basement walls to a depth of two feet below grade, and the use of a second wood door on all exterior doors containing a glass area of 10 percent or more.

Note that weatherization packages "A" through "L" do not identify any mechanical system retrofits (space heating and hot water). This is not because these retrofits are not cost effective. In fact, certain mechanical system retrofits are likely to be so cost effective that they might be undertaken in even the most basic weatherization programs. The exclusion of mechanical system retrofits is due mainly to the fact that the existing efficiency of each mechanical system must be evaluated by a heating contractor before an assessment can be made. The contractor will then provide cost estimates for potential retrofits for that particular house against which savings can be compared.

We are now ready to examine the effect of changing the values of one or more of the key decision variables on the composition of the optimum weatherization package. Throughout the discussion which follows, we will make use of the reference key presented in Table 4.6.

The results of the sensitivity analysis are presented in Table 4.7. This table is laid out in such a way that each of the 81 cases examined corresponds to a "block" or "cell". Across the top are listed the three factor levels for option cost (20 percent high, normal, and 30 percent low) and the discount rate (10 percent, 6 percent, and 3 percent). Notice that the levels of option cost examined are repeated three times. This is because we must examine <u>each</u> of the three factor levels of option cost for <u>each</u> discount rate. Across the side are listed the three factor levels for balance point (55°F, 65°F, and 70°F) and the fuel price escalation rate (0 percent short, 10 percent long; 8 percent; and 12 percent short, 4 percent long). The three factor levels of balance point are also repeated three times. This permits us to examine each of the three balance points for each estimate of the rate of increase of future fuel prices.

Examination of Table 4.7 reveals that the weatherization packages associated with an 8 percent rate of fuel price escalation (Panel 2) are almost always identical to those resulting from a 12 percent rate over the next four years followed by a 4 percent rate over the remainder of the 20 year life cycle (Panel 3). Only three cases were found in which the packages were not identical. All of these cases can be related to the assumption that the life cycle costs of the weatherization options are 20 percent higher than our estimates. For example, with a 10 percent discount rate, the use of triple glazing is cost effective with a 65°F

TABLE 4.7 RESULTS OF SENSITIVITY ANALYSIS

Fuel Price Escalation Rate		Balance Point	10% Option Cost: high	10% Option Cost: norm	10% Option Cost: low	6% Option Cost: high	6% Option Cost: norm	6% Option Cost: low	3% Option Cost: high	3% Option Cost: norm	3% Option Cost: low
Panel 1	0% short, 10% long	55°	A	A	D	A	C	E	C	D	H
		65°	C	D	D	D	D	K	D	G	L
		70°	D	D	F	D	J	L	J	J	L
Panel 2	8%	55°	A	B	E	C	D	E	D	E	K
		65°	D	D	I	D	**F**	L	J	K	L
		70°	D	F	L	F	J	L	J	L	L
Panel 3	12% short, 4% long	55°	A	B	E	B	D	E	D	E	K
		65°	C	D	I	D	F	L	F	K	L
		70°	D	F	L	F	J	L	J	L	L

F = BASELINE

balance point if the rate of fuel price escalation is 8 percent, whereas it is not cost effective if fuel prices escalate at a rate of 12 percent during the next four years and at a rate of 4 percent for the remainder of the 20 year life cycle.

Due to the similarity of the packages resulting from the 8 percent rate of fuel price escalation (Panel 2) and the 12 percent short/4 percent long (Panel 3), we may focus our atention on two fuel price escalation rate scenarios. That is, a comparison of the packages resulting from an 8 percent rate of fuel price escalation (Panel 2) with those resulting from a 0 percent short/10 percent long rate of fuel price escalation (Panel 1).

Examination of Table 4.7 reveals that the weatherization packages associated with an 8 percent fuel price escalation rate (Panel 2) tend to be larger and to increase more rapidly as the discount rate is lowered than those associated with a fuel price escalation rate of 0 percent in the next four years and 10 percent thereafter (Panel 1). There are two fairly basic explanations for this. First, the energy savings associated with a given option which occur in the first years of use and hence have the greatest value are lower with constant energy prices over the next four years than if energy prices rise at a rate of 8 percent. Even though the energy savings which occur beyond the fourth year are valued higher when the long term rate of fuel price escalation is 10 percent rather than 8 percent, they are not large enough to offset the reduced dollar savings associated with the assumption of constant energy prices in the first four years. Second, in the presence of a payback criterion, the present value of savings in the first 11 years is considerably lower under the assumption of constant energy prices followed by rapidly rising energy prices than under the assumption that energy prices increase at a rate of 8 percent. The payback constraint is thus more often binding. Therefore, some options which were cost effective over the 20 year life cycle (even with reduced dollar savings) could not satisfy the payback criterion and hence had to be excluded from the weatherization package.

We shall now examine how the baseline package compares to the "median" level of weatherization. The "median" level of weatherization is package "E" since 25 cases had lower levels and 25 cases had higher levels (including the four cases where the baseline, "F", was optimal). Focusing on Panel 1 and Panel 2 of Table 4.7, we can see that the baseline package occurs four times and that there are 29 cases where the optimal package was of a lower level than the baseline and 21 cases where the optimal package was of a higher level. Recall that weatherization packages "E" and "F" were very similar. The package which occurs most often is "D" which is also very similar to the baseline, "F". These two observations serve to highlight the fact that the level of weatherization associated with the baseline package has an additional merit in that it is, in a statistical sense, among the most probable outcomes.

A brief synopsis of the differential effect of each factor on the baseline case is presented in Table 4.8. The effects of changes of several factors in combination on the baseline case, however, are more complicated. These effects are discussed in more detail in the text which follows.

TABLE 4.8 DIFFERENTIAL EFFECT OF EACH FACTOR ON THE BASELINE WEATHERIZATION PACKAGE

Variable Conditions	Change in Condition	Change in Retrofit Package
Average Installation Costs	+ 20%	less 2nd wood door (30% glass)
	- 30%	add thermal shutter insulate attic to R-38 add R-7 basement insulation to 2 feet below grade add 2nd wood door (10% glass)
Balance Point	55°F	less 2nd wood door (30% glass)
	70°F	add thermal shutter insulate attic to R-38
Fuel Price Escalation Rate	A[1]	less 2nd wood door (30% glass)
	B[2]	no change
Discount Rate	3%	add thermal shutter insulate attic to R-38 add R-7 basement insualtion to 2 feet below grade
	10%	less 2nd wood door

[1] A refers to a 0% short and 10% long fuel price escalation rate.

[2] B refers to a 12% short and 4% long fuel price escalation rate.

Similar patterns of change in the optimal weatherization package can be seen when the two of Table 4.7 rows associated with the 70°F balance point in Panel 1 and Panel 2 are examined. For example, with 20 percent higher life-cycle costs associated with each option we have the same package with a 10 percent discount rate for both fuel price escalation rate scenarios. Furthermore, the six cases associated with a 6 percent discount rate and a 3 percent discount rate are nearly identical for both fuel price escalation rate scenarios. In most cases, however, a higher level of weatherization than given by the baseline package is indicated.

If we now focus our attention on the four remaining rows associated with the 55°F and 65°F balance points in Panel 1 and Panel 2, we can better see the effects of changing the discount rate on the optimal weatherization package. At a 10 percent discount rate weatherization package "D" occurs almost half the time. Although weatherization package "D" is of a lower level than our baseline case, "F", the two packages only differ by one option. (The baseline package includes the use of a second wood door on exterior doors containing 30 percent or more glass area.) Thus even in cases where the discount rate exceeds the fuel price escalation rate, the most likely weatherization package is revealed to be nearly identical to the baseline. This result is very important, since the rates of fuel price escalation estimated by the Department of Defense tend to be somewhat higher than those recently forecast by another Federal agency. The above statement may be easily illustrated. The present value of energy savings with a 4 percent rate of fuel price escalation and a 6 percent discount rate would be nearly identical to those associated with an 8 percent rate of fuel price escalation and a 10 percent discount rate. Replacement costs would of course be slightly higher with a 6 percent rate than with a 10 percent rate. However, quite a few of the options in the baseline package will not require replacement to achieve a 20 year life. Even in those cases where higher replacement costs are incurred (infiltration abatement and attic insulation), life-cycle savings are high enough to insure that all of the options in the baseline package are still cost effective.[1] At a 6 percent discount rate, weatherization packages "D", "E", and "F" occur in six out of the 12 possible cases. Thus once again the "baseline" package[2] is revealed to be the most likely

---

[1] If we consider the possibility of continuous changes in the level of attic insulation then the optimal level of attic insulation would be reduced slightly in going from a 10 percent discount rate to a 6 percent discount rate. (Recall that the rate of fuel price escalation is 8 percent when the discount rate is 10 percent and is 4 percent when the discount rate is 6 percent.) Since we are limiting our attic insulation choices to R-19, R-30 and R-38, however, the optimal level in this case, does not change.

[2] Quotation marks are used since the actual baseline package is "F" and not an average of "D", "E" and "F". Weatherization packages "D" and "E", however, are nearly identical to "F".

candidate as the optimal level of weatherization. When we examine the cases where a 3 percent discount rate is assumed, we find that the "baseline" case occurs in only four out of the 12 possible cases. If we ignore the cases where the weatherization options can be installed for 30 percent less than estimated, then the "baseline" package occurs in half the cases examined.

The previous discussion has demonstrated that although there is a great deal of variation in the optimal weatherization package, and although each of the four factors examined is important in determining that package, the most likely optimal weatherization package is the "baseline" weatherization package. (That is, small changes in one or more of the four key factors about the baseline figures are not likely to change the composition of the baseline package.) There are two sets of circumstances where this observation is not true. These two sets of circumstances are the assumption that (1) energy savings are based on a balance point of 70°F, and (2) the life-cycle costs of each option are 30 percent lower than estimated and future savings and costs are discounted at a rate of 3 percent.

4.4 FORECASTS FOR OTHER DEMONSTRATION SITES

Tables 4.9 through 4.11 present the forecasts for the optimal level of weatherization in each of the other 14 Demonstration Program sites.[1] Each table identifies the city, the number of degree days and the fuel type(s) and fuel price(s) used in determining the optimal level of weatherization. All forecasts presented in this section are based on the assumption that the balance point of the typical low-income residence is 65°F. Balance points based on empirical data were calculated for each house, so that use can be made of an additional set of calculations given in Appendix E. These calculations identify the optimal level of weatherization as a function of balance point. The weatherization packages which will actually be installed, however, are those presented in Tables 4.9 through 4.11.

In Tables 4.9 through 4.11 the following abbreviations are used: ALB, Albuquerque; ATL, Atlanta; CST, Charleston; CHI, Chicago; CSP, Colorado Springs; EAS, Easton; FAR, Fargo; LAS, Los Angeles; MIA, Miami; MIN, Minneapolis/St. Paul; OAK, Oakland; STL, St. Louis; TAC, Tacoma; WDC, Washington, D.C. Four symbols are also used in Table 4.9 through 4.11.

---

[1] The packages summarized in this section are based on the cost figures given in Appendix A.3 and the energy savings calculations given in Appendix B. Some minor variations from the lists presented in Tables 4.9, 4.10 and 4.11 may result, however, due to local considerations. For example, certain products may be unavailable or available only at a price significantly different from that presented in Appendix A.3. In these cases it may be necessary to modify the weatherization package somewhat. These changes are being documented and will be made available upon written request to the authors.

They are: (1) an X; (2) a blank space; (3) an A; and (4) a 2. The symbol X indicates that the option named on that now is to be installed in the city under consideration. A blank space indicates that the option named on that row is <u>not</u> to be installed in the city under consideration. The symbols A and 2 are are used only for basement wall insulation. The symbol A indicates that R-7 basement wall insulation is to be installed above grade for the city under consideration. The symbol 2 indicates that R-7 basement wall insulation is to be installed to a level of two feet below grade.

TABLE 4.9 OPTIMAL WEATHERIZATION PACKAGES FOR HOUSES HEATED BY FUEL OIL IN THE OTHER DEMONSTRATION SITES

		SITES						
		CST	CHI	EAS	FAR	MIN	TAC	WDC
	Degree Days	1904	6127	5827	9271	8310	5185	4211
OPTIONS	$/Gallon	.52	.479	.49	.469	.482	.479	.492
INFILTRATION								
Replace Broken Glass		X	X	X	X	X	X	X
Reset Glazing		X	X	X	X	X	X	X
Install New Threshold		X	X	X	X	X	X	X
Seal Structural Cracks		X	X	X	X	X	X	X
Weatherstrip Windows			X	X	X	X	X	X
Caulk Windows		X	X	X	X	X	X	X
Weatherstrip Doors			X	X	X	X	X	X
Caulk Doors			X	X	X	X	X	X
Weatherstrip Attic Hatch		X	X	X	X	X	X	X
WINDOWS								
Storm Windows								X
Storm + Film								
Storm + Shutter			X			X		
Triple Glazing				X			X	
Triple + Shutter					X			
DOORS								
Storm Door (60% Glass)				X			X	X
Second Wood Door "			X					
New Insulating Door "								
Storm Door (30% Glass)								
Second Wood Door "					X			
New Insulating Door "						X		
ATTIC								
R-11 Insulation		X						
R-19 Insulation								
R-30 Insulation			X	X			X	X
R-38 Insulation					X	X		
WALLS								
R-11 Insulation			X	X	X	X	X	X
BASEMENT WALLS								
R-7 Insulation		A	A	A	2	A	A	A

TABLE 4.10 OPTIMAL WEATHERIZATION PACKAGES FOR HOUSES HEATED BY NATURAL GAS IN THE OTHER DEMONSTRATION SITES

OPTIONS		SITES												
		ALB	ATL	CST	CHI	CSP	EAS	FAR	LAS	MIA	MIN	OAK	STL	TAC
	Degree Days	4292	3095	1904	6127	6473	5827	9271	1819	206	8310	2909	4750	5185
	$/Therm	.276	.235	.30	.263	.163	.318	.332	.20	.31	.216	.186	.273	.295
INFILTRATION														
Replace Broken Glass		X	X	X	X	X	X	X	X		X	X	X	X
Reset Glazing		X			X	X	X	X			X		X	X
Install New Threshold		X	X	X	X	X	X	X	X		X	X	X	X
Seal Structural Cracks		X	X	X	X	X	X	X	X	X	X	X	X	X
Weatherstrip Windows		X			X	X	X	X			X			X
Caulk Windows		X			X	X	X	X			X		X	X
Weatherstrip Doors		X			X		X	X			X			X
Caulk Doors		X			X	X	X	X			X		X	X
Weatherstrip Attic Hatch		X			X	X	X	X			X		X	X
WINDOWS														
Storm Windows		X			X						X		X	X
Storm + Film														
Storm + Shutter														
Triple Glazing							X							
Triple + Shutter								X						
DOORS														
Storm Door (60% Glass)														
Second Wood Door "														
New Insulating Door "														
Storm Door (30% Glass)														
Second Wood Door "								X						
New Insulating Door "														
ATTIC														
R-11 Insulation				X					X			X		
R-19 Insulation			X											
R-30 Insulation		X			X	X	X						X	X
R-38 Insulation								X			X			
WALLS														
R-11 Insulation		X			X		X	X			X		X	X
BASEMENT WALLS														
R-7 Insulation		A	A	A	A	A	A	A			A		A	A

TABLE 4.11 OPTIMAL WEATHERIZATION PACKAGES FOR HOUSES HEATED BY ELECTRICITY, PROPANE OR KEROSENE IN THE OTHER DEMONSTRATION SITES

		ELECTRICITY			PROPANE				KEROSENE
	Sites	CST	MIA	TAC	ATL	CST	CSP	WDC	WDC
	Degree Days	1904	206	5185	3095	1904	6473	4211	4211
OPTIONS	$/Unit	.037	.038	.015	.48	.49	.359	.525	.52
INFILTRATION									
Replace Broken Glass		X		X	X	X	X	X	X
Reset Glazing		X		X	X	X	X	X	X
Install New Threshold		X	X	X	X	X	X	X	X
Seal Structural Cracks		X	X	X	X	X	X	X	X
Weatherstrip Windows		X		X	X	X	X	X	X
Caulk Windows		X		X	X	X	X	X	X
Weatherstrip Doors		X		X	X	X	X	X	X
Caulk Doors		X		X	X	X	X	X	X
Weatherstrip Attic Hatch		X		X	X	X	X	X	X
WINDOWS									
Storm Windows		X	X	X					
Storm + Film								X	X
Storm + Shutter							X		
Triple Glazing					X				
Triple + Shutter									
DOORS									
Storm Door (60% Glass)					X		X		X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "								X	
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation		X				X			
R-30 Insulation			X	X	X				X
R-38 Insulation							X	X	
WALLS									
R-11 Insulation		X	X	X	X		X	X	X
BASEMENT WALLS									
R-7 Insulation		A	A	A	A	A	A	A	A

5. SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study has established a framework for systematically analyzing the economic viability of alternative methods of weatherizing low-income housing. This economic framework has been illustrated through the development of a series of forecasts (economic guidelines) which show the optimal levels of weatherization for low-income residences in 15 cities across the Nation. These economic guidelines are designed to assist the Community Services Administration in carrying out its Weatherization Demonstration Program. In particular, they are designed to achieve a more balanced level of weatherization per dollar spent. The optimal level of weatherization is balanced in the sense that for a given weatherization budget no increases in net savings can be achieved by trading one method for another.

The results of this study indicate that further research on additional topics would be useful. Further research is needed in order to refine the economic model developed in this study and to determine the optimal level of weatherization investment in low-income housing under a wider variety of circumstances. Studies which promote a fuller knowledge of how the energy consumption patterns of low-income households will change as a function of weatherization are also needed.

Of the utmost importance is the development of a methodology, based on the results of the Weatherization Demonstration Program, that will guide future weatherization activities. Ideally such a methodology would entail the development and validation of econometric models for estimating weatherization savings and costs. Such models could be tailored to the needs of the local CSA groups. Consequently these models would have the potential to identify the optimal level of weatherization in cities other than those which participated in the Weatherization Demonstration Program at points in time in the future. Another benefit of such a methodology would be to assist the CSA in the planning of its loan program for low-income homeowners. Along these lines such important questions as the size of the weatherization loan, the length of the term, and the level of subsidy required to meet desired goals could be assessed.

Previous studies have determined that significant interdependencies exist between weatherization options used to upgrade the thermal performance of the building envelope. Interdependencies are also known to exist between building envelope retrofits and mechanical system retrofits. At present only crude estimates are available for determining how these options interact. It would be helpful if better estimates were available.

More consideration might be given to alternative approaches in identifying the optimal level of weatherization. For example, optimal levels of weatherization for each balance point were calculated for each demonstration site, but the actual level of weatherization will be based on a balance point of 65°F. Additional research into how the balance point of a low-income house changes as a function of weatherization is needed. Econometric models which include empirically validated procedures for

estimating both savings and costs could then be used to identify the optimal level of weatherization under a wide variety of circumstances.

To determine the actual level of energy savings associated with each weatherization option, the performance of that option as a function of time is of the utmost importance. This issue was addressed only partially in this study and was approached indirectly through the use of future replacement costs. In essence it is assumed that the option performs as if new until the day it is replaced or the end of the study period whichever comes first. Since energy savings will be affected if the level of performance is reduced and this reduction is likely to be gradual, it is possible that the estimates of savings presented in this study may be biased upward. This bias could lead to overinvestment in energy conservation. To correct this, an attempt could be made to develop a performance function which reflects the probability that the weatherization component will not perform at the same level in the future as it does when initially installed. Ideally this performance function would incorporate information on material degradation over time as well as identify the minimal amount of maintenance required to achieve a specified level of performance.

If low-income homeowners are to bear the full cost of a loan (subsidized or not) to finance weatherization activities, it may turn out that the cost of optimum weatherization will pose unacceptable repayment burdens. In such cases (i.e., in the presence of a budget constraint), it has been recommended that all options be undertaken, but at a reduced scale.[1] One alternative to this approach, which has not been fully explored, is the use of a staged investment program. Such a program could offer a potential for generating revenues from past investments to cover the costs of future investments. Previous economic[2] and engineering[3] studies have shown that a particular mathematical analysis technique, dynamic stochastic programming, can be especially useful in the treatment of such (multiperiod capital allocation) problems. Should empirical studies reveal the presence of substantial fixed costs (i.e., the marginal cost of the first unit is quite high) associated with weatherization activities, it may be more beneficial to the homeowner to undertake only two or three options at a time at their optimal level rather than all of them at a reduced level (which would require upgrading at a future

---

[1] Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

[2] Paul A. Samuelson, "Lifetime Portfolio Selection by Dynamic Stochastic Programming," The Review of Economics and Statistics, Vo. 51, No. 3, 1969.

[3] Haim Levy and Marshall Sarnat, "The Portfolio Analysis of Multiperiod Investment Under Conditions of Risk," The Engineering Economist, Vol. 16, No. 1, 1970.

date). From a program management viewpoint, this approach is quite attractive because if dynamic stochastic programming is used, it will always be possible to identify an optimal investment policy to pursue. An additional benefit of this approach is that as the process unfolds, the level of uncertainty associated with the values of key factors in the weatherization investment decision can often be reduced. Thus regional/local CSA managers can tailor the staged investment program to address both the needs of the low-income homeowner and the goals of the CSA.

Another application of dynamic programming techniques relates to the estimation of energy savings in the presence of a block rate structure. As indicated in Chapter 4, both natural gas and electricity are usually priced in blocks. From an energy conservation viewpoint the dollar value of energy savings is closely tied to the block rate. This is because it is the marginal units of energy which are being saved. In performing the calculations presented in this study, it was not possible to determine when the discontinuities in the block rate structure were passed. To realistically do this would require that calculations on all sections of the building envelope and mechanical systems be performed simultaneously. Sizing decisions would then be made sequentially. The optimization technique known as dynamic programming fits this broad framework since it optimizes a set of decisions made sequentially. Furthermore, each decision is made in light of the consequences of past decisions. An additional advantage might result in that interdependencies among options as well as the problems posed by discontinuities in the rate structure could be accommodated. Additional research in this area could thus result in a technique which was analytically simple and more realistic than the techniques presently being used.

One of the most important questions from a policy viewpoint is how will weatherization affect the energy consumption patterns of low-income households. Since weatherization tends to make energy relatively less expensive, the families receiving it will experience a rise in real income. Expenditures resulting from this rise in real income will be divided among consumption of energy and non-energy commodities. For example, with the same family budget as before weatherization, the same household may be able to increase the thermostat setting to a level deemed more comfortable. Thus even though the family's absolute level of energy consumption has fallen, the actual level of energy consumption may be significantly greater than that anticipated as a result of optimal weatherization. Demand studies, including econometric analyses designed to estimate the price elasticity of demand for energy, are needed if policy makers are to insure that the goals of a nationwide energy conservation program for low-income households can be attained.

REFERENCES

American Institute of Architects, The House Beautiful Climate Control Project, Bulletin of the AIA, 1951.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

BASIC Language, Honeywell Software Series 400, Honeywell Information Systems, Inc., August 1971.

Baumol, William, "On the Discount Rate for Public Projects," Analysis and Evaluation of Public Expenditures: The PPB System, Joint Economic Committee, U.S. Government Printing Office, Washington, D.C., 1969.

Branson, William H., Macroeconomic Theory and Policy, Harper and Row Publishers, New York, 1972.

Chapman, Robert E. and Joseph G. Kowalski, Guidelines for Cost-Effective Lead Paint Abatement, National Bureau of Standards, Technical Note 971, January 1979.

Crenshaw, Richard, Roy Clark, Robert Chapman, Richard Grot and McClure Godette, CSA Weatherization Demonstration Project Plan, National Bureau of Standards, NBSIR 79-1706, March 1979.

Energy Conservation Investment Program Guidance, Assistant Secretary of Defense (Installations and Logistics) Memorandum, March 24, 1977.

Environmental Data Service, Climatic Atlas of the United States, U.S. Department of Commerce Report, 1968, 1974.

Godette, McClure, Installation of Architectural Options, National Bureau of Standards, Interagency Report (in press).

Grant, Eugene L. and W. Grant Ireson, Principles of Engineering Economy, Fifth Edition, The Ronald Press Company, New York, 1970.

Gressel, David, Financing Techniques for Local Rehabilitation Programs, National Association of Housing and Redevelopment Officials, Washington, D.C., 1976.

Hastings, S. Robert and Richard W. Crenshaw, Window Design Strategies to Conserve Energy, National Bureau of Standards, Building Science Series 104, June 1977.

Hirshleifer, J., Investment, Interest, and Capital, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970.

Hittle, D. C., The Building Loads Analysis and Thermodynamics (BLAST) Program Volume 1: User's Manual, U.S. Army Construction Engineering Research Laboratory, September 1977.

Hunt, Charles M., John M. Porterfield, and Paul Ondris, Air Leakage Measurements in Three Apartment Houses in the Chicago Area, National Bureau of Standards, NBSIR 78-1475, June 1978.

Kusuda, Tamami, NBSLD, The Computer Program for Heating and Cooling Loads in Buildings, National Bureau of Standards, Building Science Series 69, July 1976.

Levy, Haim, and Marshall Sarnat, "The Portfolio Analysis of Multiperiod Investment Under Conditions of Risk," The Engineering Economist, Vol. 16, No. 1, 1970.

Mayer, L.S., and Y. Benjamin, "Modelling Residential Demand for Natural Gas as a Function of the Coldness of the Month," Energy in Buildings, Vol. VI, No. 3, April 1978.

Mishan, E. J., Cost-Benefit Analysis, Praeger, Washington, 1971.

Nicholson, Walter, Microeconomic Theory: Basic Principles and Extensions, The Dryden Press, Inc., Hinsdale, Illinois, 1972.

Petersen, Stephen R., Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

Retail Prices and Indexes of Fuels and Utilities: Residential Usage, Department of Labor, Bureau of Labor Statistics, December 1977.

Robert Snow Means Company, Inc., Building Construction Cost Data 1978, Duxbury, Mass., 1978.

Ruegg, Rosalie T., John S. McConnaughey, G. Thomas Sav, and Kimberly A. Hockenbery, Life-Cycle Costing Guide for Selecting Energy Conservation Projects for Public Buildings, National Bureau of Standards, Building Science Series 113, September 1978.

Samuelson, Paul A., "Lifetime Portfolio Selection by Dynamic Stochastic Programming," The Review of Economics and Statistics, Vol. 51, No. 3, 1969.

Silberberg, Eugene, The Structure of Economics: A Mathematical Analysis, McGraw-Hill Book Company, New York, 1978.

Smith, Gerald W., Engineering Economy: Analysis of Capital Expenditures, 2nd ed., The Iowa State University Press, Ames, Iowa, 1973.

U.S. Department of Energy, "Weatherization Assistance Program for Low-Income Persons; Proposed Amendments", Federal Register, Vol. 44, No. 74, Monday, April 16, 1979.

U.S. Department of Housing and Urban Development, Final Report of the Task Force on Housing Costs, May 1978.

Weber, Stephen F., The Effect of "Resource Impact Factors" on Energy Conservation Standards for Buildings, National Bureau of Standards, Building Science Series 114, September 1978.

APPENDIX A

ESTIMATING WEATHERIZATION COSTS

Cost estimates of the architectural options used in identifying the optimal level of weatherization are developed in this appendix. Since the specifications for material selection and proper installation of the architectural options have not been fully developed, descriptions of those factors affecting the cost estimate of each weatherization option have to be made more explicit. The assumptions used in making cost estimates for each option are described and the specific cost figures used in the economic forecasting are listed. Finally, the methodology and format to be used for the collection of actual costs of specific weatherization options for the post construction evaluation of the optimization process are developed.

A.1 Description of Weatherization Options

Based on past studies with multi-family weatherization projects conducted by the University of Illinois at Chicago Circle, and literature searches for viable weatherization options for low-income housing, the following options have been selected for consideration as the architectural options in the demonstration program. The estimates for mechanical system options such as the improvement of furnace and hot water heater efficiencies are beyond the scope of the present cost estimates.

Architectural options for which estimates are presented are listed below:

<u>Windows</u>

1. Replace broken glass
2. Reset glazing in windows
3. Install storm windows
4. Install triple glazing
5. Install low emissivity film on windows
6. Weatherstrip windows
7. Caulk windows
8. Install insulating drapes (R = 1.14)
9. Install insulating shutters (R = 7.8)

<u>Doors</u>

10. Install storm door
11. Install second wood door (R = 2.18)
12. Weatherstrip exterior door
13. Caulk exterior door
14. Install new threshold

Insulation

15. Insulate walls below grade (basement and perimeter)
16. Insulate walls (R = 11) plus vapor barrier where possible)
17. Insulate attic (R = 11, 19, 30, 38)
18. Insulate floor above basement or crawl space (R = 19, 30)

General

19. Weatherstrip attic hatch
20. Seal-up structural cracks
21. Install carpet on floor
22. Close-off unused portions of house
23. Provide wind barrier around crawl space or basement walls

A.2 Assumptions Used in Making Cost Estimates

Since the level of detail associated with construction specifications for providing the weatherization options is beyond the scope of this study, it was necessary to make simplifying assumptions. The assumptions used in making cost estimates for all options are stated as follows.

Cost estimates for the weatherization options were primarily collected from the local community action groups or local contractors recommended by the community action group, and supplemented by construction suppliers' catalogues, department store catalogues and the 1978 Means Building Construction Cost Data[1] guide. Each local community action group identified whether the weatherization options will be carried out through the use of CETA labor or furnished and installed by a local building contractor.

1. All estimates shown are "in-place" prices which include labor, material, overhead and profit.

2. Each estimate shown is the unit price for one option only.

3. Estimates used for selecting energy conservation options are only of the order of magnitude. Actual installation prices will have to be collected and tabulated during the demonstration phase of the weatherization project.

4. Estimates are shown in dollar per square foot or linear foot for each item. These unit prices can be easily compared with the benefit side of energy conservation since the reductions of energy use are also expressed in the same units.

---

[1] Building Construction Cost Data 1978, Robert Snow Means Company, Inc., Duxbury, Mass., 1978.

Specific assumptions for estimating each weatherization option are listed as follows.

1. <u>Replace broken glass in windows</u>: $\$/Ft^2$
   Remove broken glass and old glazing, cut new plate glass to fit existing opening and install glass. It is assumed that 24" x 24" size of glass would be the most common stock size from which the replacement pane is to be cut.

2. <u>Reset glazing in windows</u>: $/Ft
   Apply glazing compound on outside and inside of existing window panes to make them weatherproof. A window size of 3 ft by 5 ft is assumed.

3. <u>Install storm windows</u>: $\$/Ft^2$
   Furnish and install a triple track storm window of up to 15 square feet in size. Screen is included. No special preparation on existing surfaces to receive the storm window is required.

4. <u>Provide triple glazing for windows</u>: $\$/Ft^2$
   Install a new storm window up to 3 ft by 5 ft size inside the existing window and storm window.

5. <u>Install low emissivity films</u>: $\$/Ft^2$
   "Lockspraygold" or equivalent applied to the entire glass area of the window.[1]

6. <u>Weatherstrip windows</u>: $/Ft
   Any weatherstripping material which is available in local hardware and specialty stores.

7. <u>Caulk windows</u>: $/Ft
   Use suitable sealant or caulking compound for exterior weatherproof caulking

8. <u>Install insulating lining over existing window drapes</u>: $\$/Ft^2$
   "Roclon" insulated drapery lining ($1.80 per yard of 48" width).

9. <u>Install insulating shutters over windows</u>: $\$/Ft^2$
   Install on the interior side of the window to reduce heat losses. Composed of 1-1/2" thick insulation sandwiched between 1/4" thick plywood with R value = 7. Price includes hinges, trim, and finish painting.

10. <u>Install storm door</u>: $\$/Ft^2$
    Furnish and install a storm door of approximately 3' x 7' in size.

---

[1] Identification of commercial products is included only to adequately specify the procedure. Identification does not imply recommendation or endorsement by the National Bureau of Standards.

11. Install 2nd wood door: $/Ft^2
Install a standard grade exterior wood door. Installation will be either on the inside or outside of the existing door depending on the direction of swing of the existing door.

12. Replace exterior door with insulating door: $/Ft^2
Furnish and install a commercially available insulating door. It shall have a minimum of R6 rating.

13. Weatherstrip exterior door: $/Ft
Any door weatherstripping material which is available in local hardware and specialty stores.

14. Caulk exterior door: $/Ft
Use suitable sealant or exterior weatherproof caulking.

15. Install new threshold: $/Ft
Furnish and install a new threshold that is compatible with the exterior door.

16A. Install insulation below grade of a first floor slab: $/Ft^2
Excavate, attach 2" styrofoam with adhesive to the edge of slab and footing. Make the exposed surface fireproof. Backfill to existing grade. 18" to 20" deep insulation is estimated.

16B. Install interior wall insulation for basement walls: $/Ft^2
Apply furring to the basement wall. Install 2" styrofoam. Install 3/8" thick drywall. Taping and painting are not included.

17A. Install interior wall insulation over solid masonry wall: $/Ft^2
Provide furring, install 2" thick styrofoam or 3-1/2" fiberglass insulation. Install dry wall. Provide wood base. Tape and paint walls with damp-proof paint.

17B. Install exterior wall insulation over solid masonry wall: $/Ft^2
Install "Drive-it" over exterior wall.

17C. Provide insulation (R-11) in existing wood framed walls: $/Ft^2
Fill frame walls with loose fill or other insulation by inserting an applicator through the exterior side of the wall. Plug and paint with two coats of vapor barrier paint.

17D. Provide insulation (R-11) in existing veneer wall: $/Ft^2
Similar to assumption for 17C.

18. Insulate attic: $/Ft^2
Furnish and install loose fill or blanket insulation to satisfy R11, R30, R38 values. Install attic vents where needed.

19. Provide floor insulation: $/Ft^2
Provide blanket insulation to satisfy R19 and R30 values.

20. <u>Weatherstrip attic hatch</u>: \$/Ft
Furnish and install locally available weatherstripping to make the attic hatch weather-tight.

21A. <u>Seal up Structural Cracks on Masonry Walls</u>: $\$/Ft^2$
Provide "tuck-pointing" for a square foot area.

21B. <u>Seal up Structural cracks on Wood Siding Walls</u>: $\$/Ft^2$
Replace with similar siding and paint to match for a square foot of area.

21C. <u>Seal up Structural Cracks on Veneer Wall</u>: $\$/Ft^2$
Provide "tuck-pointing" for a square foot area.

22. <u>Carpet floor</u>: $\$/Ft^2$
Provide floor carpet.

23. <u>Close-off unused portion of house</u>
Seal and tape existing interior doors.

24. <u>Provide wind barrier around crawl space or basement wall</u>
Design specifically for an individual situation.

A.3 Cost Figures Used in Economic Forecasts

Following are the cost estimates for providing these weatherization options in 15 cities. The First Cost is the cost incurred at the time of the installation of the option. The 20 Year Cost includes the cost of maintenance and anticipated replacement throughout the time period of analysis.

In Tables A.1 and A.2 the following abbreviations are used: ALB, Albuquerque; ATL, Atlanta; CST, Charleston; CHI, Chicago; CSP, Colorado Springs; EAS, Easton; FAR, Fargo; LAS, Los Angeles; MIA, Miami; MIN, Minneapolis/St. Paul; OAK, Oakland; POR, Portland; STL, St. Louis; TAC, Tacoma; WDC, Washington, D.C.

A.4 Format and Methodology for Cost Data Collection

The collection of accurate cost information is of crucial importance in the weatherization demonstration program. A good set of detailed cost information is needed to verify the weatherization option selection process and to provide a sound basis for future weatherization planning and budgeting. The "optimal" weatherization package weighs expected energy savings against the cost of the options. However, the "optimal" weatherization packages actually being installed are based on forecasts which of necessity rely on simplifying assumptions. Similarly, the expected energy savings figures are based on calculations which include additional simplifying assumptions (see Appendix B). As a result, the information collected in the field, on both actual cost and actual energy

TABLE A.1 ESTIMATES OF FIRST COSTS USED IN THE ECONOMIC ANALYSES BY SITE

Architectural Option															
Infiltration	ALB	ATL	CST	CHI	CSP	EAS	FAR	LAS	MIA	MIN	OAK	POR	STL	TAC	WDC
Replace Broken Glass in Window	7.00	7.00	5.00	10.00	8.50	6.00	8.00	5.00	7.00	8.00	9.00	6.30	6.30	6.20	4.76
Reset Glazing in Window	0.50	0.40	0.37	0.35	0.50	0.38	0.65	0.35	0.30	0.45	0.50	0.39	0.35	0.40	0.40
Install New Threshold	4.00	4.00	6.00	3.50	6.00	4.34	6.00	4.00	3.00	9.00	5.00	6.00	8.00	5.67	4.67
Seal Structural Cracks - Frame	0.90	0.90	0.80	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	0.80	1.00	1.00	1.25
Seal Structural Cracks - Masonry	1.20	1.50	1.30	1.60	1.50	1.30	1.30	--	1.20	--	1.30	1.60	1.30	--	2.00
Seal Structural Cracks - Veneer	1.20	1.50	1.30	1.60	1.60	1.30	1.30	--	1.20	--	1.30	1.60	1.30	--	2.00
Weatherstrip Windows	0.50	0.40	0.42	0.35	0.50	0.34	0.40	0.30	0.30	0.50	0.50	0.40	0.63	0.34	0.32
Caulk Windows	0.40	0.40	0.34	0.35	0.25	0.24	0.34	0.25	0.30	0.35	0.50	0.30	0.30	0.29	0.25
Weatherstrip Doors	0.40	0.40	0.42	0.35	0.50	0.33	0.42	0.30	0.30	0.40	0.50	0.40	0.63	0.38	0.41
Caulk Doors	0.40	0.40	0.34	0.35	0.25	0.24	0.33	0.25	0.30	0.35	0.50	0.30	0.30	0.22	0.25
Weatherstrip Attic Hatch	0.40	0.40	0.42	0.35	0.50	0.34	0.42	0.50	0.30	0.50	0.50	0.40	0.60	0.38	0.58
Window Options															
Install Standard Storm Window	2.00	2.25	2.83	3.00	3.00	2.37	2.40	2.62	2.62	3.25	2.62	2.40	2.20	2.62	1.50
Install Insulating Drape	1.00	1.00	1.50	1.00	1.20	1.50	1.50	1.50	1.50	1.00	1.00	1.50	1.50	1.50	1.00
Install Insulating Shutter	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	4.00
Install Window Film	1.50	1.50	1.70	1.50	1.50	1.70	1.70	1.50	1.50	1.50	1.50	1.70	1.70	1.70	1.25
Provide Triple Glazing	4.00	4.50	5.66	6.00	6.00	4.74	4.80	5.24	5.24	6.50	5.24	4.80	4.40	5.24	7.00
Door Options															
Install Storm Door	3.60	3.00	6.00	6.00	3.50	4.25	4.00	6.00	3.75	6.00	3.75	4.00	4.00	3.50	3.25
Install 2nd Wood Door	5.50	5.50	6.50	6.50	5.50	6.50	5.20	6.50	5.50	6.50	5.50	5.20	5.20	6.50	4.76
Replace Door w/Insulating Door	6.50	6.50	9.50	7.00	6.50	9.50	5.70	9.50	6.50	6.00	6.50	5.70	5.70	9.50	7.14
Attic Insulation															
R-11	0.25	0.20	0.15	0.25	0.24	0.14	0.19	0.20	0.15	0.35	0.15	0.17	0.17	0.14	0.24
R-19	0.35	0.30	0.28	0.35	0.32	0.27	0.32	0.30	0.20	0.45	0.25	0.30	0.30	0.24	0.32
R-30	0.45	0.40	0.41	0.45	0.40	0.40	0.45	0.45	0.30	0.55	0.35	0.43	0.43	0.34	0.40
R-38	0.55	0.50	0.54	0.58	0.48	0.53	0.58	0.58	0.40	0.60	0.45	0.56	0.56	0.44	0.48
Wall Insulation															
R-11: Frame	0.80	0.80	0.85	1.00	0.90	0.80	0.90	1.33	1.04	1.00	1.04	0.80	0.80	0.85	0.75
R-11: Masonry	1.20	1.50	--	1.50	1.50	1.30	1.50	--	--	--	--	--	1.30	--	1.00
R-11: Veneer	1.20	--	0.85	0.90	0.90	0.80	0.90	--	--	--	--	--	0.80	--	1.00
Basement Insulation															
R-7	0.70	0.70	0.70	0.75	0.70	0.70	0.70	0.75	0.65	0.75	0.70	0.70	0.70	0.70	0.70

TABLE A.2 ESTIMATES OF 20 YEAR COSTS USED IN THE ECONOMIC ANALYSES BY SITE

Architectural Option	DEMONSTRATION SITE														
Infiltration Options	ALB	ATL	CST	CHI	CSP	EAS	FAR	LAS	MIA	MIN	OAK	POR	STL	TAC	WDC
Replace Broken Glass in Window	7.10	7.10	5.07	10.14	8.62	6.08	8.11	5.07	7.10	8.11	9.13	6.39	6.39	6.29	4.83
Reset Glazing in Window	0.53	0.42	0.39	0.37	0.53	0.40	0.69	0.37	0.32	0.48	0.53	0.41	0.37	0.42	0.42
Install New Threshold	6.23	6.23	9.35	5.45	9.35	6.76	9.35	6.23	4.68	14.03	7.79	9.35	12.47	8.84	7.28
Seal Structursl Cracks - Frame	0.90	0.90	0.80	1.00	1.00	1.00	1.00	1.00	0.80	1.00	1.00	0.80	1.00	1.00	1.25
Seal Structural Cracks - Masonry	1.20	1.50	1.30	1.60	1.50	1.30	1.30	—	1.20	--	.30	1.60	1.30	—	2.00
Seal Structural Cracks - Veneer	1.20	1.50	1.30	1.60	1.60	1.30	1.30	—	1.20	--	1.30	1.60	1.30	—	2.00
Weatherstrip Windows	0.57	0.46	0.48	0.40	0.57	0.39	0.46	0.34	0.34	0.57	0.57	0.46	0.72	0.39	0.36
Caulk Windows	0.50	0.50	0.43	0.44	0.31	0.30	0.43	0.31	0.38	0.44	0.63	0.38	0.38	0.36	0.31
Weatherstrip Doors	0.57	0.57	0.60	0.50	0.72	0.47	0.60	0.43	0.43	0.57	0.72	0.57	0.90	0.54	0.59
Caulk Doors	0.51	0.51	0.43	0.45	0.32	0.31	0.42	0.32	0.38	0.45	0.64	0.38	0.38	0.28	0.32
Weatherstrip Attic Hatch	0.57	0.57	0.60	0.50	0.71	0.48	0.60	0.71	0.43	0.71	0.71	0.57	0.85	0.54	0.82
Window Options															
Install Standard Storm Widow	2.00	2.25	2.83	3.00	3.00	2.37	2.40	2.62	2.62	3.25	2.62	2.40	2.20	2.62	1.50
Install Insulating Drape	1.56	1.56	2.34	1.56	1.87	2.34	2.34	2.34	2.34	1.56	1.56	2.34	2.34	2.34	1.56
Install Insulating Shutter	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	4.00
Install Window Film	2.91	2.91	3.30	2.91	2.91	3.30	3.30	2.91	2.91	2.91	2.91	3.30	3.30	3.30	2.43
Provide Triple Glazing	4.00	4.50	5.66	6.00	6.00	4.74	4.80	5.24	5.24	6.50	5.24	4.80	4.40	5.24	7.00
Door Options															
Install Storm Door	4.10	3.42	6.84	6.84	3.99	4.64	4.56	6.84	4.27	6.84	4.27	4.56	4.56	3.99	3.70
Install 2nd Wood Door	5.50	5.50	6.50	6.50	5.50	6.50	5.20	6.50	5.50	6.50	5.50	5.20	5.20	6.50	4.76
Replace Door w/Insulating Door	6.50	6.50	9.50	7.00	6.50	9.50	5.70	9.50	6.50	6.00	6.50	5.70	5.70	9.50	7.14
Attic Insulation															
R-11	0.28	0.22	0.17	0.28	0.27	0.15	0.21	0.22	0.17	0.39	0.17	0.19	0.17	0.15	0.27
R-19	0.39	0.33	0.31	0.39	0.35	0.30	0.35	0.33	0.22	0.50	0.28	0.33	0.33	0.27	0.35
R-30	0.50	0.44	0.45	0.50	0.44	0.44	0.50	0.50	0.33	0.61	0.39	0.47	0.47	0.38	0.44
R-38	0.61	0.55	0.60	0.64	0.53	0.59	0.64	0.64	0.44	0.66	0.50	0.62	0.62	0.49	0.53
Wall Insulation															
R-11: Frame	0.80	0.80	0.85	1.00	0.90	0.80	0.90	1.33	1.04	1.00	1.04	0.80	0.80	0.85	0.75
R-11: Masonry	1.20	1.50	—	1.50	1.50	1.30	1.50	--	--	--	--	—	1.30	--	1.00
R-11: Veneer	1.20	—	0.85	0.90	0.90	0.80	0.90	--	--	--	--	—	0.80	—	1.00
Basement Insulation															
R-7	0.70	0.70	0.70	0.75	0.70	0.70	0.70	0.75	0.65	0.75	0.70	0.70	0.70	0.70	0.70

savings, may indicate that greater cost effectiveness could be achieved if a different combination of weatherization options were installed. Thus, in order to improve the chance of identifying the most cost-effective combination of weatherization options for future programs, it is necessary to develop a cost estimation procedure which permits "real world" considerations such as the size of the dwelling unit, the condition of the different building elements, and the wage rates paid to workers doing the weatherization job to enter into the cost calculations. The use of this procedure should permit the achievement of more weatherization per dollar spent. This should permit field offices to operate with greater flexibility in the future in budgeting and forecasting program costs, so that more houses can have the most cost-effective combination of weatherization options installed.

The types of cost data which were of interest to the weatherization demonstration program were discussed in Section 3.1. Briefly, they include payments to labor, payments for materials, equipment rentals and any overhead costs or profits that should in principle be assigned to the weatherization task. Those costs that the contractor or CSA Agency incurs if it undertakes a specific job are called <u>direct costs</u>. Those costs that the contractor or CSA Agency incurs regardless of whether it undertakes a specific job or not are called <u>overhead costs</u>. The difference between the <u>bid price</u>, the contract amount for which the contractor agreed to do the work, and direct costs and overhead costs represents the contractor's <u>pretax profits</u>. Also of interest is the size of the contractor's <u>markup</u>. The bid price divided by the sum of the direct costs in the contract yields one plus the fractional markup. Markup, therefore, includes both overhead costs and pretax profits.

Table A.3 summarizes the cost data required to meet these needs.

TABLE A.3 COST DATA COLLECTION: REPORTING REQUIREMENTS

Type of Cost	Reporting Requirements
Bid Price	Each Contract*
Direct Costs*	
Labor	
Direct Labor	Each Option, Each Dwelling Unit
Indirect Labor	Each Contract
Materials	Each Option, Each Dwelling Unit
Equipment	Each Option, Each Dwelling Unit

*Contracts should be numbered, for example from 1 to N, so that all direct costs associated with that contract can be traced back to the parent contract.

Now that we have seen the types of cost data which are to be collected, we can review the way in which they will be collected. Our past experiences indicate that better quality cost information can be collected if one member of the research staff is assigned as coordinator and meets with contractors on a regular basis.[1] This facilitates control of the operation and helps in determining the appropriate action to be taken if any cost information is found to be lacking. It is not desirable to wait until the contract has been completed to request the cost data, since the reliability of the data will then depend more on the contractor's memory rather than on documented figures.

Two basic cost data collection forms are used. The first form is concerned with direct labor, material, and equipment charges (Exhibits A.1 and A.2). This form will be filled out by the local CSA representative for <u>each weatherization option and for each dwelling unit</u>. The second form is concerned with indirect labor charges (Exhibits A.3 and A.4). This form will be filled out by the local CSA representative for <u>each contract</u>.

Let us first consider the form (Exhibit A.1) for recording the direct costs for labor, materials, and special equipment. Notice that on the form there is a space for the street address of the dwelling unit (along with the street address, a contract ID number should also be entered). Additional information includes: when the work was started and when it was finished; the building element to which the option was applied; and the name of the option. Beneath this information are listed three types of work which can be performed: (1) preparation, (2) installation, and (3) other. Associated with each of these types of work are direct labor charges and materials used and/or equipment rented. Direct labor charges are identified by skill type, for example, carpenter, painter, laborer. The number of hours expended in the task for each skill type is then entered, for example; 8 hours for the carpenter, 3 hours for the painter, 10 hours for the laborer. The hourly wage rate is then entered in the third column, for each skill type.[2] Also associated with each of the three types of work are material and special equipment usages. This information facilitates the identification of the material and equipment needs associated with the installation of the various weatherization options. In the first column, the type of material or equipment is identified, for example, caulking compound. The second column is to record the unit size, for example, 20 oz. tube. The third column is for either the time in use (for special equipment, such as blowers or heaters) or the quantity used, for example, 7 tubes.

---

[1] Robert E. Chapman and Joseph G. Kowalski, <u>Guidelines for Cost-Effective Lead Paint Abatement</u>, National Bureau of Standards Technical Note 971, January 1979.

[2] The program does not intend that any individual be identified; our focus is on determining the role that labor inputs play in causing costs to vary and not on determining the wage or productivity of any individual.

EXHIBIT A.1 DWELLING UNIT COST DATA FORM

DWELLING UNIT COST DATA FORM

ADDRESS ____________________ RETROFIT OPTION ____________________

BUILDING ELEMENT ____________________ SQ FT, LIN FT, #UNITS ____________________

TOTAL COST

TYPE OF WORK	DIRECT LABOR USE				MATERIALS & EQUIPMENT USE				
	LABOR SKILL	HOURS	RATE	TOTAL	MATERIALS/EQUIPMENT	UNIT SIZE	TIME OR QUANTITY	UNIT COST	TOTAL
PREPARATION									
TOTAL									
INSTALLATION									
TOTAL									
OTHER									
TOTAL									

EXHIBIT A.2

TYPE OF WORK DEFINITIONS

PREPARATION

Those tasks which must be done prior to the actual installation of the weatherization option. This category includes tasks such as job set up and any necessary repairs to or replacement of building elements. Preparation should not include indirect labor costs.

INSTALLATION

Those tasks that are involved in the normal installation process for the particular weatherization option. This includes such activities as finish painting and clean up.

OTHER

Those taks which are not normally involved in the installation of the particular weatherization option. This category is different from "preparation" in that it includes such tasks as equipment repairs and work stoppage.

EXHIBIT A.3
INDIRECT LABOR COSTS DATA FORM

CONTRACT NUMBER ________

INDIRECT COST ITEM		LABOR TYPE 1		LABOR TYPE 2		LABOR TYPE 3		OTHER	
DESCRIPTION	ID#	WAGE	HOURS	WAGE	HOURS	WAGE	HOURS	COST	AMOUNT

EXHIBIT A.4

CONTRACT SPECIFIC INDIRECT COSTS

Indirect labor costs are those costs which can not be linked to a specific weatherization option. Below is a list (not exhaustive) of the kinds of indirect labor costs that may be associated with the installation of the weatherization options.

1. Travel time
2. Down time
3. Clean-up time (if not attributable to a specific weatherization option)
4. Equipment costs (if not attributable to a specific weatherization option).

The final column contains the unit cost, or rental rate, for the material or equipment, for example, $2.00 per tube. Additional information about filling out the form is given on the back of the form (see Exhibit A.2).

Exhibit A.3 displays the data collection form for recording "indirect labor cost." This form is not required for each option and each dwelling unit. It is only necessary to complete one indirect labor cost form for each contract. However, since indirect labor costs will occur irregularly (for example, downtime because the dwelling unit occupants may not be at home), these costs should be recorded on the form when they happen, in order to avoid reporting errors due to faulty recall. The first column of the indirect labor cost data form asks for a brief description of the indirect cost item. A dwelling unit ID number, if possible, is also reported along with the brief description. For example, one might find in this column, "Travel time between dwelling units 34 and 35." There follow three columns labeled "labor" with sub-headings for wage rates and hours. This enables differing labor rates to be associated with the described item. (If more than three categories of labor are involved, the next line can be used.) A fourth column headed by "other" is also included in order to capture related costs other than labor. For example, "Travel-time between dwelling units 34 and 35," may involve the cost of operating a vehicle used in that period. On the back side of this form, Exhibit A.4, a brief definition of indirect labor cost is given. Also on the back are a few examples of indirect labor costs that are likely to arise.

APPENDIX B

ESTIMATING WEATHERIZATION SAVINGS

The purpose of this appendix is to provide background and technical information on the calculations used to estimate weatherization savings. Three basic types of of calculations are discussed. These calculations concern: (1) infiltration options; (2) conduction options; and (3) mechanical system options. Savings associated with the first category, infiltration options, are based on reductions in the number of air changes per hour. In the second category, savings due to increased thermal resistance are based on load estimates expressed in Btu's per square foot per year. Btu energy savings per square foot are then derived by examining the differential loads associated with a given retrofit. In the final category, savings due to improved mechanical system efficiencies are expressed in percentage savings on the building load after the shell has been weatherized. In all cases life-cycle dollar savings are calculated and used as input to the investment analysis discussed in Appendix C. Let us now examine each set of calculations.

B.1 Infiltration Calculations

Energy savings from reductions in the number of air changes per hour are expressed as the number of Btus per square foot or per linear foot per year for each option. All calculations assume the specific heat of air to be 0.24 and the density of air in pounds per cubic foot to be 0.075. The building being examined is assumed to have a volume of 12,000 cubic feet and to contain 344 linear feet of doors and window sashes. Infiltration savings for each option based on the above assumptions are given in Table B.1. The term DD_a used in the load calculations presented in Table B.1 refers to the number of degree days per year for a given balance point at a given location.[1] The term HD, which enters into the calculation of savings from replacing the threshold and broken glass and of sealing up structural cracks refers to the average number of heating days per year for a given location.

[1] The balance point is that outdoor temperature below which a supply of heat to the conditioned space is needed in order to maintain a given indoor temperature. Throughout this study the temperature in the conditioned space is assumed to be 70°F. A balance point was calculated for each dwelling unit in the Demonstration Program. It was determined based on the best fit straight line between energy consumption data and degree days. By the nature of this relationship, calculations based on the balance point permit a more accurate measure of anticipated savings. Those readers interested in a more detailed discussion of the balance point concept and its effect on the optimal level of weatherization are referred to Appendix E.

TABLE B.1 ENERGY SAVINGS DUE TO REDUCTIONS IN INFILTRATION LOSSES[a]

Retrofit	Units of Savings	Yearly Savings
Replace Threshold	$Btu/Ft^2/year$	$[0.24 \times 0.075 \times DD_a \times 24] \times [300 + 22 \times DD_a/HD]$
Seal up Structural Cracks	$Btu/Ft^2/year$	
Replace Broken Glass	$Btu/Ft^2/year$	$[0.24 \times 0.075 \times DD_a \times 24] \times [30 + 22 \times DD_a/HD]$
Reset Glazing	Btu/Ft/Year	$[0.24 \times 0.075 \times DD_a \times 24] \times [\frac{0.1 \times 12000}{344}]$
Weatherstrip Windows	Btu/Ft/Year	
Caulk Windows	Btu/Ft/Year	
Weatherstrip Doors	Btu/Ft/Year	
Caulk Doors	Btu/Ft/Year	
Weatherstrip Attic Hatch	Btu/Ft/Year	

Source: Charles M. Hunt, John M. Porterfield, and Paul Ondris, Air Leakage Measurements in Three Apartment Houses in the Chicago Area, National Bureau of Standards, NBSIR 78-1475, June 1978.

B.2 Conduction Calculations

In order to calculate estimated energy savings in Btu's per square foot per year due to reductions in conductive losses, a series of steps must be followed. First, the base load per square foot of envelope section is calculated. Next, as the resistance of the envelope section is increased, reductions in the initial base load are estimated. (These reductions or load differentials are the Btu savings associated with the retrofit option.) Finally, if the resistance of the envelope section can be varied incrementally (e.g., attic insulation), the difference in the load between increments must also be examined. This approach facilitates the marginal analysis which is undertaken to identify the optimal level of weatherization investment for each option.

In estimating energy savings through increased thermal resistance it is also important to take into consideration the effect of selective management practices used by the occupant. For example, shutters are usually closed only at night. Thus the resulting increases in thermal resistance over the glazed portions of the window accrue only during the nighttime hours. To deal explicitly with the potential for window management, or any other special cases, degree days during the nighttime hours for a given balance point and location (DD_c) and degree days during the day for a given balance point and location (DD_d) were calculated. Two sets of degree day figures based on the average temperature of the basement were calculated. The difference in temperatures in the conditioned space and the basement result in degree day category DD_e. The number of indoor-outdoor basement degree days is denoted DD_f; this category of degree days is used only in cases where floor insulation is being assessed.

Since there are a large number of potential window options, the alternative window retrofits had to be examined in stages. The load calculations associated with each stage and each retrofit are coded and identified in Table B.2. Btu savings based on these calculations (see Table B.2) are summarized (using the retrofit code) in Table B.3. Note that these figures are based on differential loads. In order to get dollar savings, the product of the equivalent energy cost per therm and the differential load expressed in therms is multiplied by a present value factor.

Load and energy savings calculations for doors, attic insulation, wall insulation, and basement wall insulation, are given in Tables B.4 and B.5, B.6 and B.7, B.8 and B.9, and B.10 and B.11 respectively. Notice that in Table B.7, both total and incremental savings are calculated. Total savings are needed to calculate how long the option takes to pay for itself whereas incremental savings are needed to determine the optimum level of weatherization. These topics are discussed in more detail in Appendix C.

TABLE B.2 LOAD CALCULATIONS ASSOCIATED WITH WINDOW RETROFITS

Retrofit		Code	Load in $Btu/Ft^2/year$
STAGE 1			
BASE:	Uninsulated window[a] (single glazing)	A	$1.13 \times DD_a \times 24$
	Storm Window[a] (Double glazing)	B	$0.56 \times DD_a \times 24$
	Managed Insulating Drapes[b]		
	Night	C_N	$0.80 \times DD_c \times 24$
	Day	C_D	$1.13 \times DD_d \times 24$
	Total	C	$C_N + C_D$
	Managed Shutters[b]		
	Night	D_N	$0.13 \times DD_c \times 24$
	Day	D_D	$1.13 \times DD_d \times 24$
	Total	D	$D_N + D_D$
	Low Emissivity Film	E	$0.74 \times DD_a \times 24$
STAGE 2			
	Storm Window and Drapes		
	Night	BC_N	$0.48 \times DD_c \times 24$
	Day	BC_D	$0.56 \times DD_d \times 24$
	Total	BC	$BC_N + BC_D$
	Storm Window and Shutter	BD_N	$0.12 \times DD_c \times 24$
	Day	BD_D	$0.56 \times DD_d \times 24$
	Total	BD	$BD_N + BD_D$
	Storm Window and Film	BE	$0.38 \times DD_a \times 24$
	Triple Glazing	BB	$0.36 \times DD_a \times 24$

STAGE 3

Triple Glazing and Drapes		
Night	BBC_N	$0.32 \times DD_c \times 24$
Day	BBC_D	$0.36 \times DD_d \times 24$
Total	BBC	$BBC_N + BBC_D$
Triple Glazing and Shutters		
Night	BBD_N	$0.10 \times DD_c \times 24$
Day	BBD_D	$0.36 \times DD_d \times 24$
Total	BBD	$BBD_N + BBD_D$
Triple Glazing and Film	BBE	$0.28 \times DD_a \times 24$

[a] Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

[b] Source: S. Robert Hastings and Richard W. Crenshaw, Window Design Strategies to Conserve Energy, National Bureau of Standards, Building Science Series 104, June 1977.

TABLE B.3 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH WINDOW RETROFITS[a]

Retrofit	Savings in Btu/Ft^2/Year
STAGE 1[b]	
Storm Windows (Double Glazing)	A - B
Managed Insulating Drapes	A - C
Managed Shutters	A - D
Low Emissivity Film	A - E
STAGE 2[c]	
Storm Windows and Drapes	B - BC
Storm Windows and Shutters	B - BD
Storm Windows and Film	B - BE
Triple Glazing	B - BB
STAGE 3[d]	
Triple Glazing and Drapes	BB - BBC
Triple Glazing and Shutters	BB - BBD
Triple Glazing and Film	BB - BBE

[a] The letters in the second column refer to calculations presented in Table B.2.

[b] Base: Single Glazing

[c] Base: Double Glazing

[d] Base: Triple Glazing

TABLE B.4 LOAD CALCULATIONS ASSOCIATED WITH DOOR RETROFITS[a]

Retrofit	Code	Load in $Btu/Ft^2/Year$
Base: Existing 1-3/4" Solid Door	A	$0.457 \times DD_a \times 24$
Storm Door	B	$0.31 \times DD_a \times 24$
Second Wood Door	C	$0.20 \times DD_a \times 24$
Insulating Door	D	$0.17 \times DD_a \times 24$

[a] Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

TABLE B.5 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH DOOR RETROFITS[a]

Retrofit	Savings in $Btu/Ft^2/Year$
Storm Door	A - B
Second Wood Door	A - C
Insulating Door	A - D

[a] The letters in the second column refer to calculations presented in Table B.4.

TABLE B.6 LOAD CALCULATIONS ASSOCIATED WITH ATTIC INSULATION[a]

Retrofit	Code	Load in $Btu/Ft^2/Year$
Base: Uninsulated attic	A	$0.19 \times DD_a \times 24$
R-11 Insulation	B	$0.065 \times DD_a \times 24$
R-19 Insulation	C	$0.044 \times DD_a \times 24$
R-30 Insulation	D	$0.031 \times DD_a \times 24$
R-38 Insulation	E	$0.025 \times DD_a \times 24$

[a] Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

TABLE B.7 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH ATTIC INSULATION[a]

Retrofit	Total Savings in $Btu/Ft^2/Year$	Incremental Savings in $Btu/Ft^2/Year$
R-11 Insulation	A - B	A - B
R-19 Insulation	A - C	B - C
R-30 Insulation	A - D	C - D
R-38 Insulation	A - E	D - E

[a] The letters in the second and third columns refer to calculations presented in Table B.6.

TABLE B.8 LOAD CALCULATIONS ASSOCIATED WITH WALL INSULATION[a]

Retrofit	Code	Load in Btu/Ft^2/Year
Base 1: Uninsulated Masonry Wall	A1	$0.39 \times DD_a \times 24$
R-11 in Masonry Wall	B1	$0.08 \times DD_a \times 24$
Base 2: Uninsulated Frame Wall	A2	$0.22 \times DD_a \times 24$
R-11 in Frame Wall	B2	$0.069 \times DD_a \times 24$
Base 3: Uninsulated Veneer Wall	A3	$0.33 \times DD_a \times 24$
R-11 in Veneer Wall	B3	$0.077 \times DD_a \times 24$

[a] Source: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., ASHRAE Handbook of Fundamentals, New York, 1972.

TABLE B.9 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH WALL INSULATION[a]

Retrofit	Savings in Btu/Ft^2/Year
R-11 in Masonry Wall	A1 - B1
R-11 in Frame Wall	A2 - B2
R-11 in Veneer Wall	A3 - B3

[a] The letters in the second column refer to calculations presented in Table B.8.

TABLE B.10 LOAD CALCULATIONS ASSOCIATED WITH BASEMENT WALLS

Retrofit	Code	Load in Btu/Ft^2/Year
Base 1: Uninsulated Basement Wall above grade	A1	$0.78 \times DD_b \times 24$
R-7 above grade	B1	$0.121 \times DD_b \times 24$
Base 2: Uninsulated Basement Wall below grade	A2	$0.113 \times DD_b \times 24$
R-7 below grade	B2	$0.058 \times DD_b \times 24$

TABLE B.11 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH BASEMENT WALLS[a]

Retrofit	Savings in Btu/Ft^2/Year
R-7 above grade	A1 - B1
R-7 below grade	A2 - B2

[a] The letters in the second column refer to calculations presented in Table B.10.

The load and energy savings calculations for first floor insulation differ slightly from those presented above (see Table B.12). This is because first floor insulation is examined in two stages. In the first stage, R-19, R-30 and floor carpet are analyzed independently (see Table B.13). In the second stage the economic viability of floor carpet is analyzed on the assumption that either R-19 or R-30 floor insulation has been installed. Incremental analyses are conducted at each stage to determine the optimal level of first floor insulation.

B.3 Mechanical System Retrofits

The types of mechanical options which are being considered for installation in each weatherized house can be classified as: a) those that affect the building load, b) those that affect the efficiency of the furnace, c) those that affect the efficiency of the heat distribution system, and d) those that reduce the amount of energy used for supplying domestic hot water. The mechanical options intrinsically differ from the architectural options in that, though the savings which they produce are dependent on the total load of the dwelling, the cost of installing an option is usually load independent. Second, the amount of savings that can be obtained from most mechanical options depends on the initial condition of the mechanical system. For example, it is not possible to predict the savings that would result from replacing a burner or a furnace unless the present efficiency of the burner or furnace is known.

In order to simplify the selection processes and to reduce problems attributable to interdependence, the architectural options and the mechanical options have been separated. As a means of insuring that only those weatherization options which are cost-effective are installed, engineering judgment was used to establish several ground rules for limiting the impact of system interdependencies. These ground rules focused: (1) in the case of the architectural options, on anticipated system efficiency improvement; and (2) in the case of mechanical system options, on reduced loads due to the improved thermal performance of the building envelope.

Specifically the two types of options are separated by assuming a conservative overall mechanical efficiency of 65 percent for oil, 70 percent for gas, and 100 percent for electricity in selecting architectural options, and then selecting the mechanical options to satisfy the reduced thermal load based on the "post" retrofit levels of the architectural options.

In order to decide what options are to be installed in a given house, a series of tests are first performed, and the efficiency of the existing system determined. Each option that can be added to the existing system is then assigned an efficiency improvement value (EIV) based on the efficiency of the existing system plus any improvements already incorporated. The improvement value is then multiplied by the load of the building after architectural retrofit to determine the energy savings. The change

TABLE B.13 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH FLOOR INSULATION[a]

Retrofit	Total Savings in $Btu/Ft^2/Year$	Incremental Savings in $Btu/Ft^2/Year$
STAGE 1		
R19 in floor	A - B	A - B
R30 in floor	A - C	B - C
Carpet on floor	A - D	A - D
STAGE 2		
R19 and Carpet	A - BD	B - BD
R30 and Carpet	A - CD	C - CD

[a] The letters in the second and third columns refer to calculations presented in Table B.12.

TABLE B.13 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH FLOOR INSULATIONS[a]

Retrofit	Total Savings in $Btu/Ft^2/Year$	Incremental Savings in $Btu/Ft^2/Year$
STAGE 1		
R19 in floor	A - B	A - B
R30 in floor	A - C	B - C
Carpet on floor	A - D	A - D
STAGE 2		
R19 and Carpet	A - BD	B - BD
R30 and Carpet	A - CD	C - CD

[a] The letters in the second and third columns refer to calculations presented in Table B.12.

TABLE B.14 VALUES FOR DEGREE DAYS A THROUGH E AND HEATING DAYS USED IN FORECASTS

City	Degree Days A	Degree Days B	Degree Days C	Degree Days D	Degree Days E	Heating Days	District[a] Heating Factor
Albuquerque	4292	2818	2788	1504	3107	239	1.03008
Atlanta	3095	2545	2012	1083	1568	196	0.74280
Charleston	1904	1904	1341	563	795	159	0.45696
Chicago	6127	2976	3410	2717	5120	256	1.47048
Colorado Springs	6473	2749	4018	2455	5817	277	1.55352
Easton	5827	2750	3348	2479	4902	258	1.39848
Fargo	9271	3758	5041	4230	8323	287	2.22504
Los Angeles	1819	1018	1336	483	2034	226	0.43656
Miami	206	206	183	23	160	32	0.04944
Minneapolis/St. Paul	8310	3859	4539	3771	6552	273	1.99440
Oakland	2909	975	1884	1024	4438	317	0.69816
Portland	7493	3648	4202	3291	6060	303	1.79832
St. Louis	4750	3040	2778	1972	3164	226	1.14000
Tacoma	5185	1544	2972	2213	6042	318	1.24440
Washington, D.C.	4211	2633	2546	1665	3402	243	1.01064

[a] U.S. Department of Energy, "Weatherization Assistance Program for Low-Income Persons; Proposed Amendments," Federal Register, Vol. 44, No. 74, Monday, April 16, 1979.

in load due to the EIV expressed in dollars over the life cycle is then compared to the cost of the option. Savings-to-cost ratios for the 20 year study period are then computed.

The resulting list of possible options for the particular house is ranked by savings to cost ratio, with the largest savings-to-cost ratio first. The remaining list of mechanical system retrofits are then reranked based on the assumption that the first option has been installed. Working down from the top of the list, enough options are selected such that their combined EIV is equal to the difference between the efficiency of the existing system and the potential efficiency of that system. That is, they will bring the efficiency of the existing system up to the theoretical optimum of 65 percent for oil, 70 percent for gas, and 100 percent for electricity. The benefits in energy saved are then compared to the cost of the combination of mechanical options to insure that they pay for themselves in 11 years.[1] Table B.15 defines the terms used in estimating energy savings due to mechanical system retrofits. Table B.16 summarizes the calculations used in the economic analysis.

[1] The selection of mechanical options differs from the selection of the architectural options in that each mechanical option represents an increment. Thus each mechanical option is assessed incrementally using a 20 year life cycle. The whole set of mechanical options, or the mechanical system, is then tested against the 11 year payback constraint. If the constraint is violated, then the mechanical system retrofit package is resized in the same way as for the architectural options.

B.15 DEFINITION OF TERMS USED IN MECHANICAL SYSTEM RETROFIT CALCULATIONS

L_a = .50 times the yearly Btu load on the house as determined from utility bills.

e_a = annual efficiency of the furnace before modification or replacement.

e_b = annual efficiency of the furnace after modification or replacement.

D = square feet of duct to be insulated.

V_a = U-value of duct after insulation.

V_b = U-value of duct before insulation.

n = percent reduction due to nighttime temperature setback.

e_{aR} = measured recovery efficiency for water heater from mechanical system test data.

e_{NR} = recovery efficiency of new water heater.

e_n = recovery efficiency of water heater.

B.16 ENERGY SAVINGS CALCULATIONS ASSOCIATED WITH MECHANICAL SYSTEM RETROFITS

Retrofit	Yearly Savings (Btu/year)	
Flue or Vent Damper or Restrictor	$.07 \times L_a$	
Electronic Ignition	$.05 \times L_a$	
Derate Furnace	$.046 \times L_a$	
Replace Burner or Furnace	$L_a \left(\frac{1}{e_b} - \frac{1}{e_a}\right)$	
Insulate Ducts	$D \, (V_a - V_b)$	
Radiator Reflector	Assumed effective on exterior wall if annual heating degree days greater than 4000	
Night Setback Thermostat	$L_a \times n/100$	
Relocate Thermostat	Estimated on house-by-house basis	
Insulate Water Heater	Electric	1,245,745
	Gas	3,650,000
	Oil	3,570,000
Aquabooster	$.124 \times L_a$	
Replace Water Heater	$13.78 \times 10^6/\left(\frac{1}{e_{aR}} - \frac{1}{e_{NR}}\right)$	
Thermostat Setting	Gas	3,650,000
(150-130° F)	Oil	3,570,000
Reduce Water Heater	Electric	1,245,745
Shower Flow Resistors	$7.55 \, (F-2.5) \times 10^5/e_N$	
Timer on Electric Water Heaters	6,399,375	

APPENDIX C

SELECTED TOPICS IN INVESTMENT THEORY

In this appendix we shall explore several topics in investment theory which provide the technical underpinnings for identifying the optimal level of weatherization.

C.1 The Present Discounted Value Criterion

Generally speaking, investment today is undertaken in order to increase consumption in some future time period. The rate of return associated with the investment may be interpreted as a measure of the terms at which consumption today may be turned into consumption tomorrow. Since the future holds uncertainty, the rate of return acts as a signal to individuals to withhold some output from current consumption and as a rationing device to limit investment opportunities. The rate of return may therefore be used to relate individual tastes and available technology. First let us relate graphically the technical possibilities of transforming consumption today, C_o, into consumption in the future, C_f. For a given technology and with available resources, the possible combination of C_o and C_f are similar to those shown in Figure C.1. The concavity of the curve is based on the assumption that there is a diminishing rate of trade-off of C_o for C_f as present consumption, C_o, increases. More precisely, the marginal rate of transformation diminishes. The slope of the curve at any point, A, shows how consumption can be technically traded between the present and the future. The slope of the curve at any point A may also be regarded as the rate of return on the investment. Let us now introduce a set of indifference curves which relate individual tastes or preferences for present and future consumption. Along each indifference curve we have all those combinations of present consumption and future consumption which leave the individual equally well off. The slope of the indifference curve at any point shows how for the individual's tastes, present consumption may be substituted for future consumption while leaving the consumer equally well-off. Indifference curves are assumed to be convex, that is, as present consumption increases, the marginal rate of substitution decreases. As an individual moves up and to the right he becomes better off. In our analysis, we shall assume that each individual seeks to maximize his/her well-being by moving to the highest indifference curve attainable. In Figure C.2 we see that the highest indifference curve attainable is I_1 which is just tangent to our investment opportunity curve at A. (In this case the individual relies solely on his own productive opportunity.) At A the marginal rate of substitution (the slope of the indifference curve) is equal to the marginal rate of transformation (the slope of the investment opportunity curve). The slope of both curves at A is $-(1 + r)$ where r is the rate of return on the investment. Notice that this individual has a high preference for current consumption. This result would be expected in low-income households.

FIGURE C.1 INVESTMENT OPPORTUNITY FRONTIER

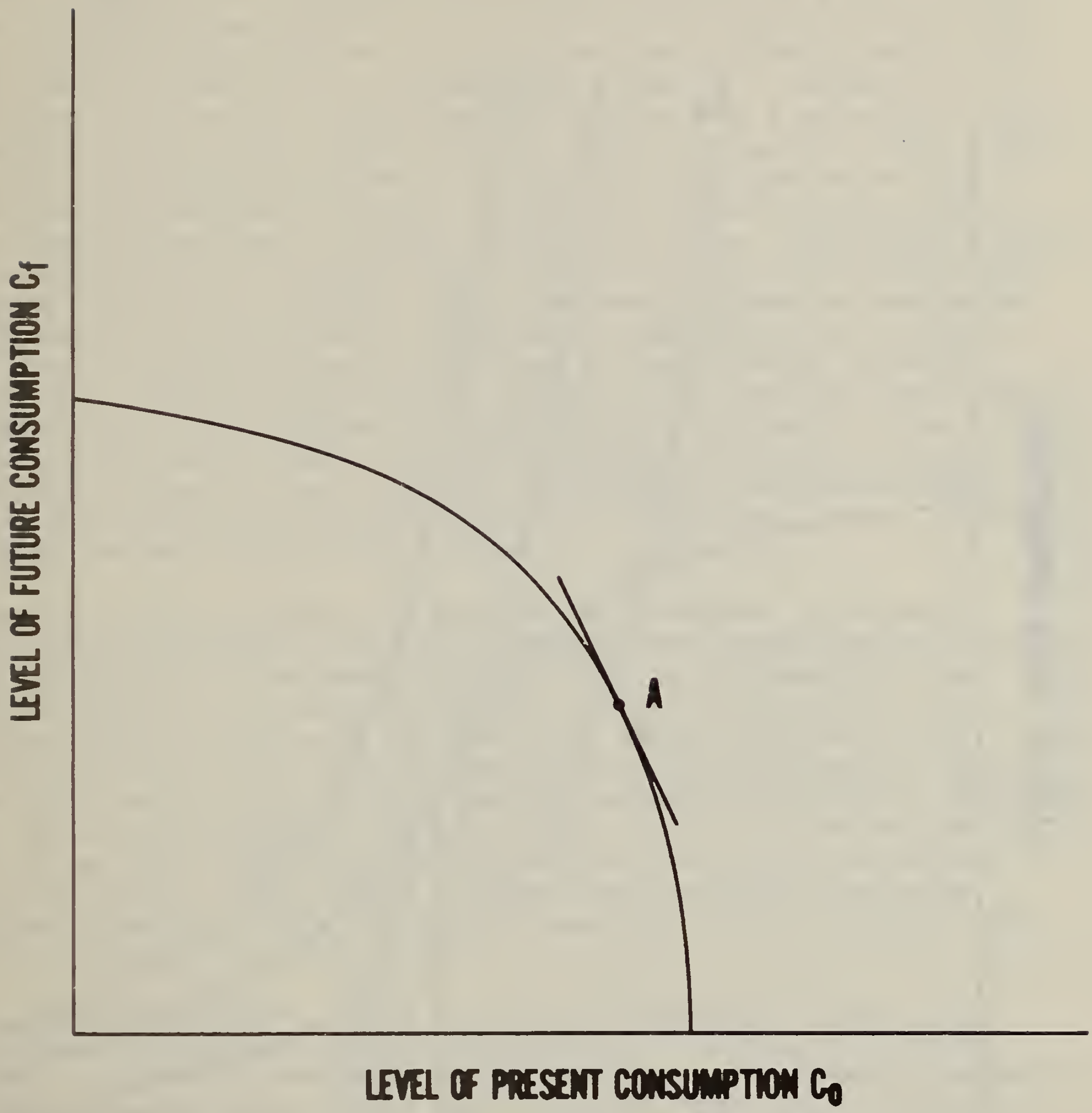
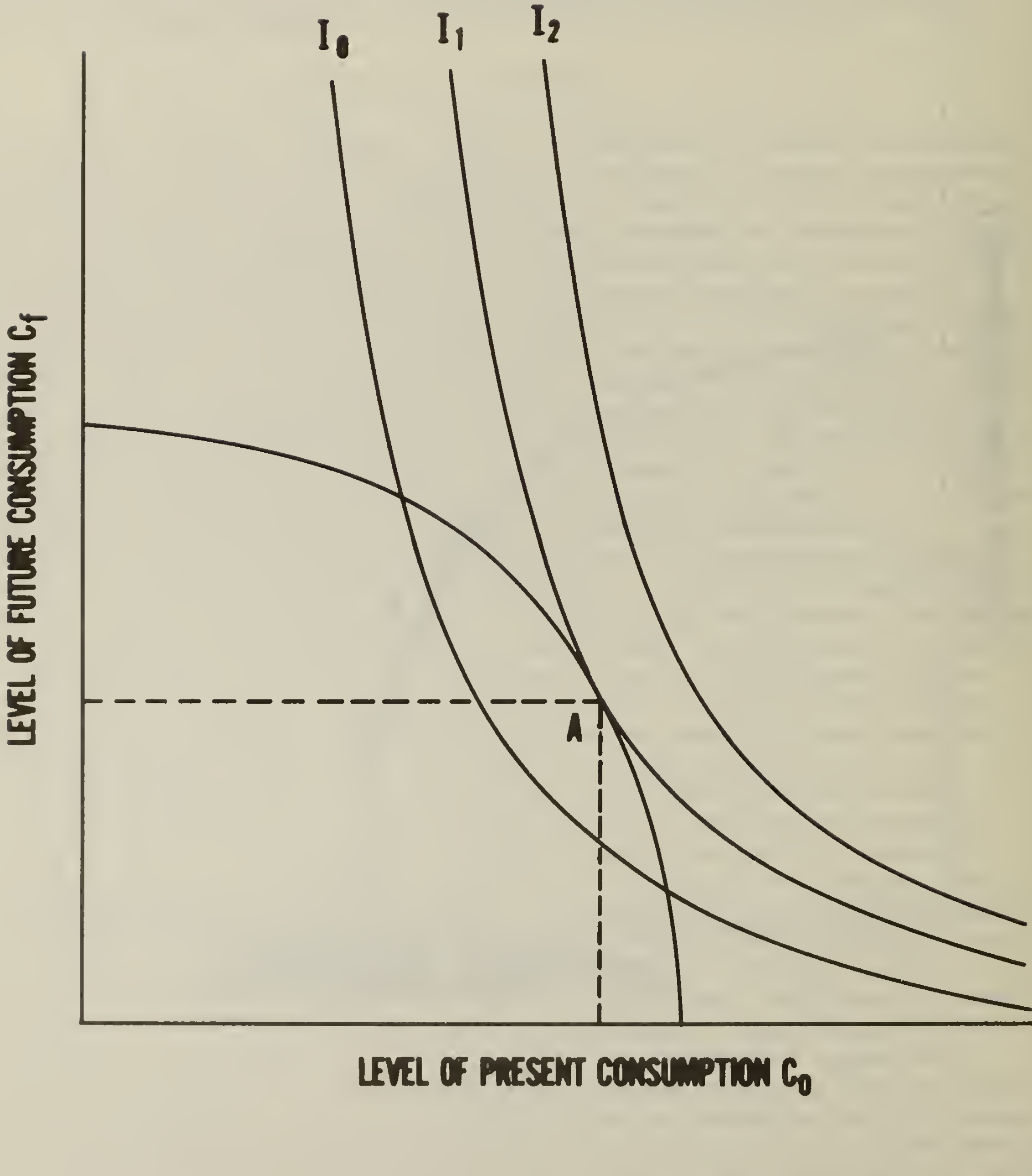


FIGURE C.2 EQUILIBRIUM BETWEEN PRESENT AND FUTURE CONSUMPTION



Suppose now that the individual can borrow money at some market rate r_o. We wish to see if a higher indifference curve can be reached by such borrowing. Furthermore, let us assume that r_o is less than r. The slope on our borrowing curve is $-(1 + r)$. This curve is shown in Figure C.3 to be tangent to our investment opportunity frontier at B and to be tangent to indifference curve I_1 at C. That is, the individual uses their own productive opportunities to reach B and then borrows to end up at C. Note that the individual is better off at C than at A because he is on a higher indifference curve. Since poor people have a relatively strong preference for current consumption over future consumption, their indifference curves constrain them to a relatively steep portion of their investment opportunity frontier. However, by borrowing even if rates are high they can reach a higher indifference curve. This argument helps to explain why poorer families often incur substantial borrowing debts. Suppose that we now introduce a new investment alternative, weatherization, and that the loan may be financed at a market rate of interest, r_w, where r_w is less than r_o. The slope of the borrowing curve is $-(1 + r_w)$. The borrowing curve is tangent to the investment opportunity frontier at D and is tangent to indifference curve I_3 at E. From Figure C.3 we can see that with weatherization investments the low-income homeowner is able to reach a higher indifference curve than by either borrowing or relying on his own productive opportunities (i.e., staying on the investment opportunity frontier).

Earlier it was stated that the shape of the investment opportunity frontier was determined under the assumption that technology was fixed. The introduction of weatherization opportunities is essentially an introduction of a new technology to the low-income homeowner. This change affects the shape of the investment opportunity frontier by shifting portions of it upward. Figure C.4 shows the effect of changing technology on the shape of the investment opportunity frontier. Here the curve shifts from CC to CC' and finally to CC". If we were now to draw in our indifference curves, we would see that a new equilibrium position results. Also, since the investment opportunity curve has shifted upward it is possible for the homeowner to reach a higher indifference curve.

Let us now examine what effect a payback constraint will have on the shape of our investment opportunity frontier. A payback requirement serves to constrain investment opportunities. It also biases investment decisions toward those options which maintain a high level of current consumption. That is, in the presence of a payback constraint for a given level of current consumption C_o, a lower level of future consumption (C_f') will result than if no payback constraint were imposed (C_f''). This point is illustrated graphically in Figure C.5 where the investment opportunity frontier is CC' in the presence of a payback constraint and CC" with the payback constraint removed. Furthermore, if we were to put in our borrowing line we would see that it is tangent to CC' at A' and to CC" at A". The highest indifference curves that can be reached are then I_1 and I_2 at B' and B" respectively. If we extend the borrowing

FIGURE C.5 THE EFFECTS OF A PAYBACK CONSTRAINT ON EQUILIBRIUM

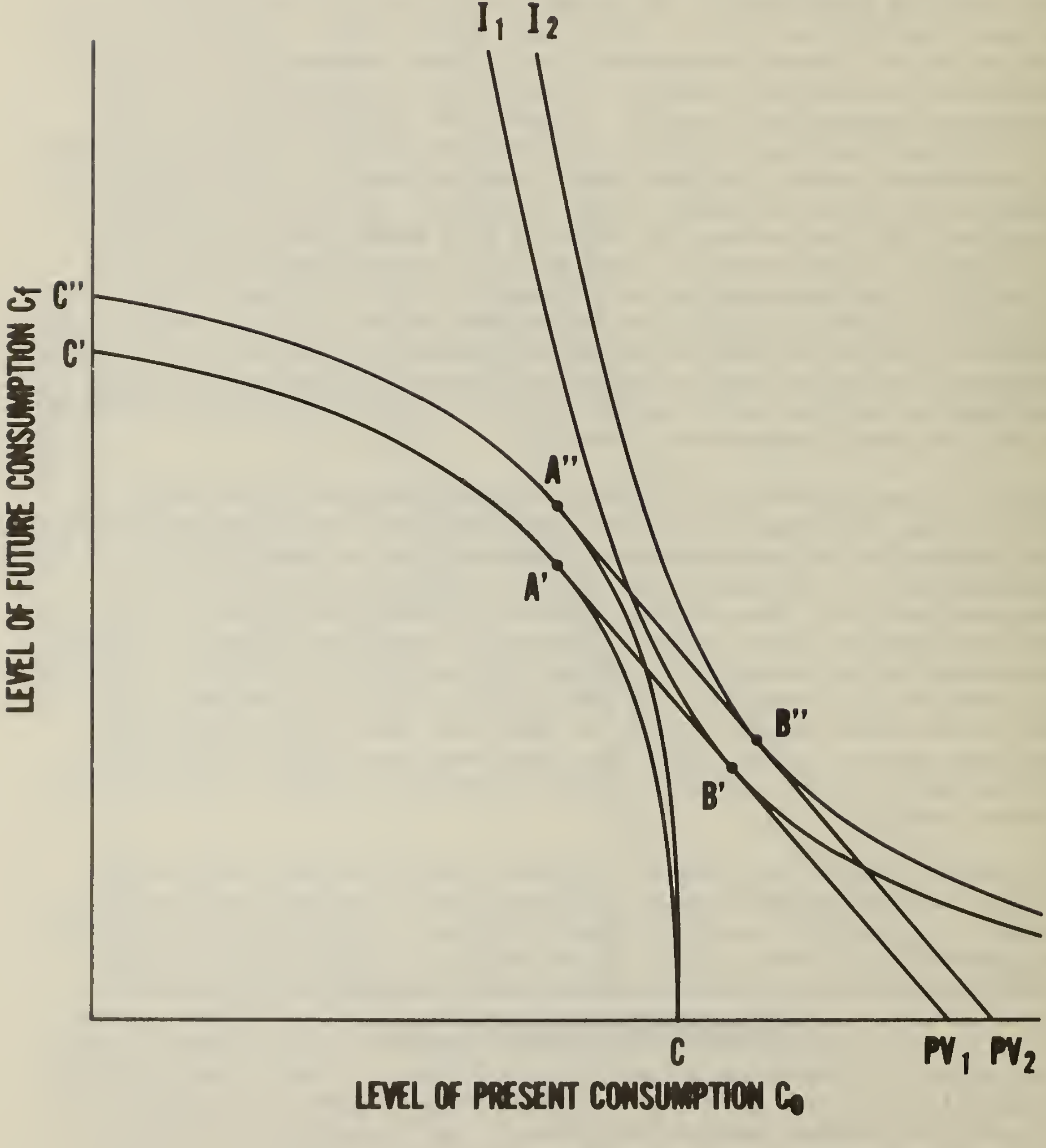


FIGURE C.4 THE EFFECTS OF CHANGING TECHNOLOGY ON THE SHAPE OF THE INVESTMENT OPPORTUNITY FRONTIER

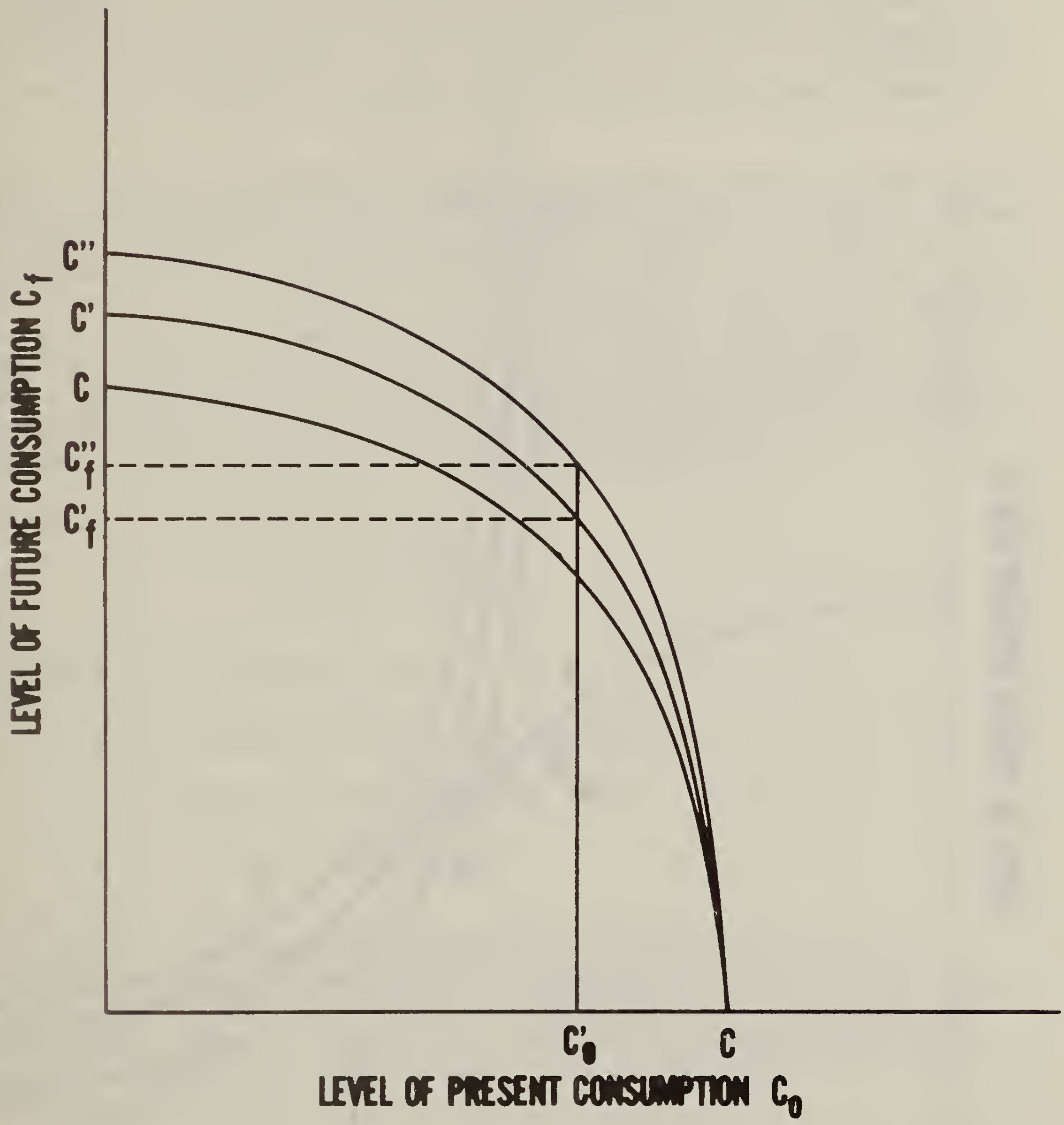
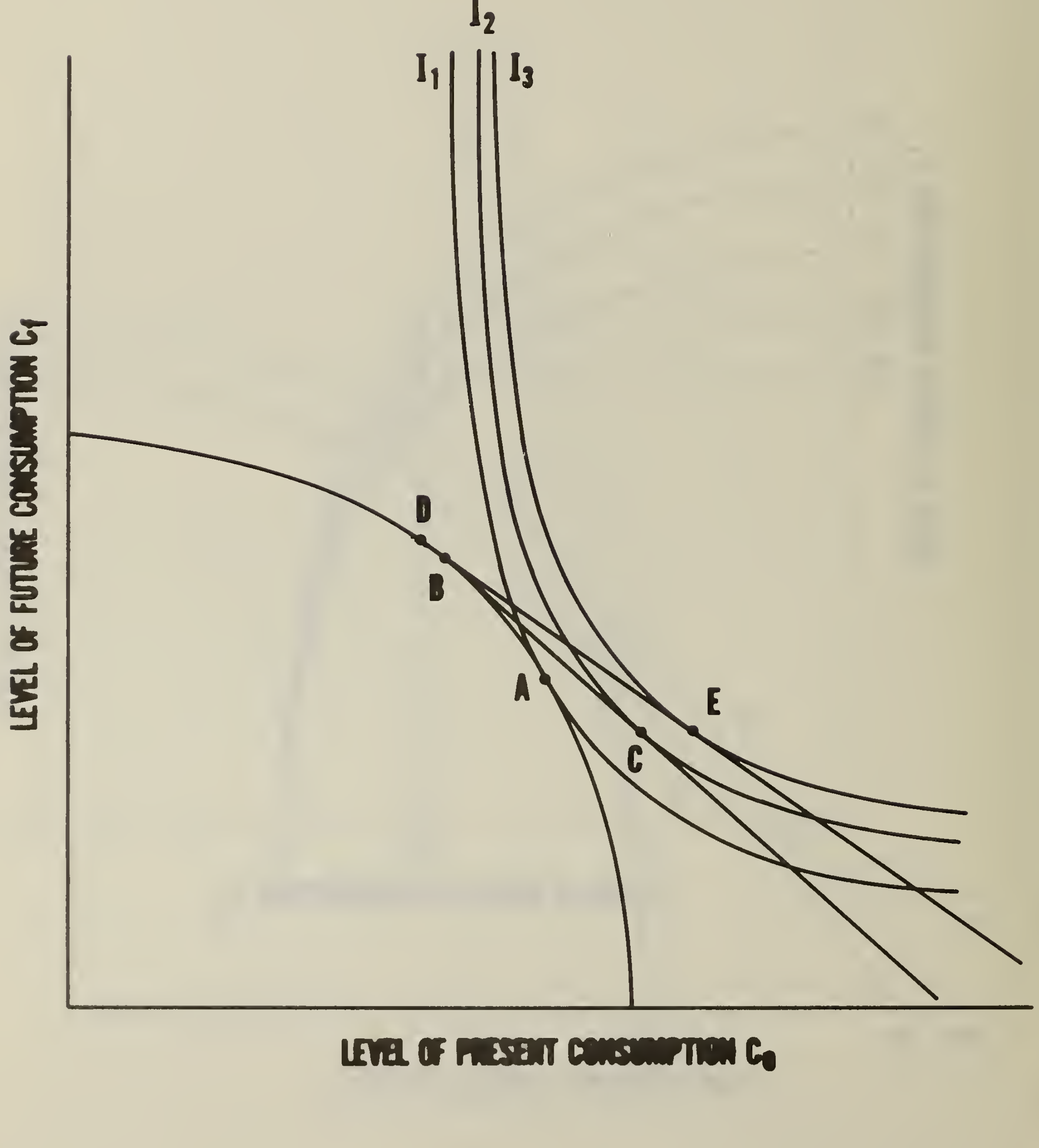


FIGURE C.3 EQUILIBRIUM BETWEEN PRESENT AND FUTURE CONSUMPTION WHEN BORROWING IS PERMITTED



line until it reaches the horizontal axis, as is done in Figure C.5, we can calculate the present value of the investment. Notice that in the presence of a payback constraint, the borrowing curve intersects the horizontal axis at PV_1. In the case where no payback constraint is imposed the present value of the investment is PV_2. It can readily be seen that PV_2 is greater than PV_1, so that imposing a payback reduces the present value of the investment.

What is being portrayed in Figure C.5 is the process through which investors maximize present value while maximizing their utility. It has been shown elsewhere[1] that maximizing present value will result in equating the marginal rate of transformation along the investment opportunity frontier to the marginal rate of substitution along the indifference curve. This is a basic condition for economic efficiency. Note that in our previous discussion a two period model was used for expository clarity. The generalization from two periods to N periods is straightforward but rather tedious. More succinctly, we may define the (net) present value of an investment, j, over N periods to be

$$PV_j = - C^j{}_o + \sum_{t=1}^{N} \frac{(S^j{}_t - C^j{}_t)}{(1 + D)^t}$$

where D = the discount rate;

$C^j{}_o$ = the initial cost of the project;

$S^j{}_t$ = savings in the t^{th} period; and

$C^j{}_t$ = costs in the t^{th} period.

(For the reader interested in a rigorous formulation, the text by Hirshleifer is highly recommended.[2]) Maximizing present value is therefore equivalent to selecting only those investments, j, for which PV_j is greater than zero. If there are J of these investments then the quantity to be maximized, MPV, of the investor's present value may be expressed mathematically as

$$MPV = \sum_{j=1}^{J} PV_j.$$

---

[1] William H. Branson, Macroeconomic Theory and Policy, Harper and Row, Publishers, New York, 1972.

[2] J. Hirshleifer, Investment, Interest, and Capital, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1970.

As was stated earlier, maximizing present value will maximize welfare. We saw that in the presence of a payback criterion present value and hence welfare was not maximized. Other investment criteria which do not maximize present value will not maximize welfare. Let us now examine a commonly used investment criterion which maximizes present value.

C.2 OPTIMIZING WEATHERIZATION INVESTMENTS

In this section we shall review several economic concepts which permit us to identify that level of weatherization which is optimal. In particular, we shall focus on how life-cycle cost techniques enable us to choose among options as well as what effect the presence of a payback constraint has on weatherization investments.

Cost-benefit analysis provides the basic framework for an economic analysis of alternative weatherization options. That is, by the systematic weighing of available alternatives cost-benefit analysis establishes guidelines for increasing the efficiency of resource allocation.[1] The emphasis in this study will be on those portions of cost-benefit analysis which permit us to choose among investment opportunities of varying size.

The principles of cost-benefit analysis actually used in this study are, to a great extent, based on microeconomic theory. It is through microeconomic theory and its treatment of profit maximization and marginalism that the necessary criteria for optimizing weatherization investments are established. An illustration of how these two microeconomic concepts are used in practice is now in order. In the next paragraph parenthetical terms refer to the application of microeconomic concept to weatherization specifically. The general microeconomic terminology immediately procedes the parenthetical term.

A firm's profits (household's net savings) are defined as its total revenues (total savings) minus its total costs. In this case we shall assume that both revenues and costs are a function of the level of output (weatherization). Microeconomic theory then requires for profits to be maximized that the additional revenue on the last unit sold (marginal revenue) be equal to the additional cost of producing that unit (marginal costs).

Clearly total weatherization costs and total energy savings are a function of the level of energy conservation. Net savings, the difference between the total savings and total costs, is therefore directly analogous to a firm's profit. If we denote total savings as $S(\ell)$ and total costs as $C(\ell)$, where ℓ is the level of energy conservation, then net savings, $NS(\ell)$, is defined as

$$NS(\ell) = S(\ell) - C(\ell). \qquad \text{C.1}$$

---

[1] For a thorough treatment of cost-benefit analysis see E. J. Mishan, Cost-Benefit Analysis, Praeger, Washington, 1971.

It is net savings, $NS(\ell)$, that the homeowner wishes to maximize. Having specified this relationship, calculus may now be used to maximize the homeowner's net savings. Differentiating equation C.1 with respect to ℓ results in

$$NS'(\ell) = S'(\ell) - C'(\ell).$$

Equating $NS'(\ell)$ to zero gives a necessary condition for maximizing $NS(\ell)$, namely that the optimum level of weatherization is that level, ℓ, at which

$$S'(\ell) = C'(\ell).$$

In other words, net savings are maximized when marginal savings, $S'(\ell)$, are equal to marginal costs, $C'(\ell)$. That is, the savings generated by the last increment of weatherization are just equal to the costs of that increment.[1]

Thus far no mention has been made of either the length of the study period or how future cost or savings considerations are to be treated. These costs and savings, although more difficult to quantify, must be included in the consumer's decision to invest in weatherization. The requirement that all relevant costs which occur over the study period be taken into consideration leads to the use of life-cycle cost techniques. Life-cycle cost techniques may be defined as techniques which explicitly treat the cost (negative cash flows) of purchasing, installing, operating, maintaining and repairing a specific weatherization option as well as the expected savings (positive cash flows) associated with that option which occur over the entire study period. Life-cycle cost techniques are particularly useful since they enable us to analyze the merits of alternative weatherization options and make tradeoffs between competing alternatives.

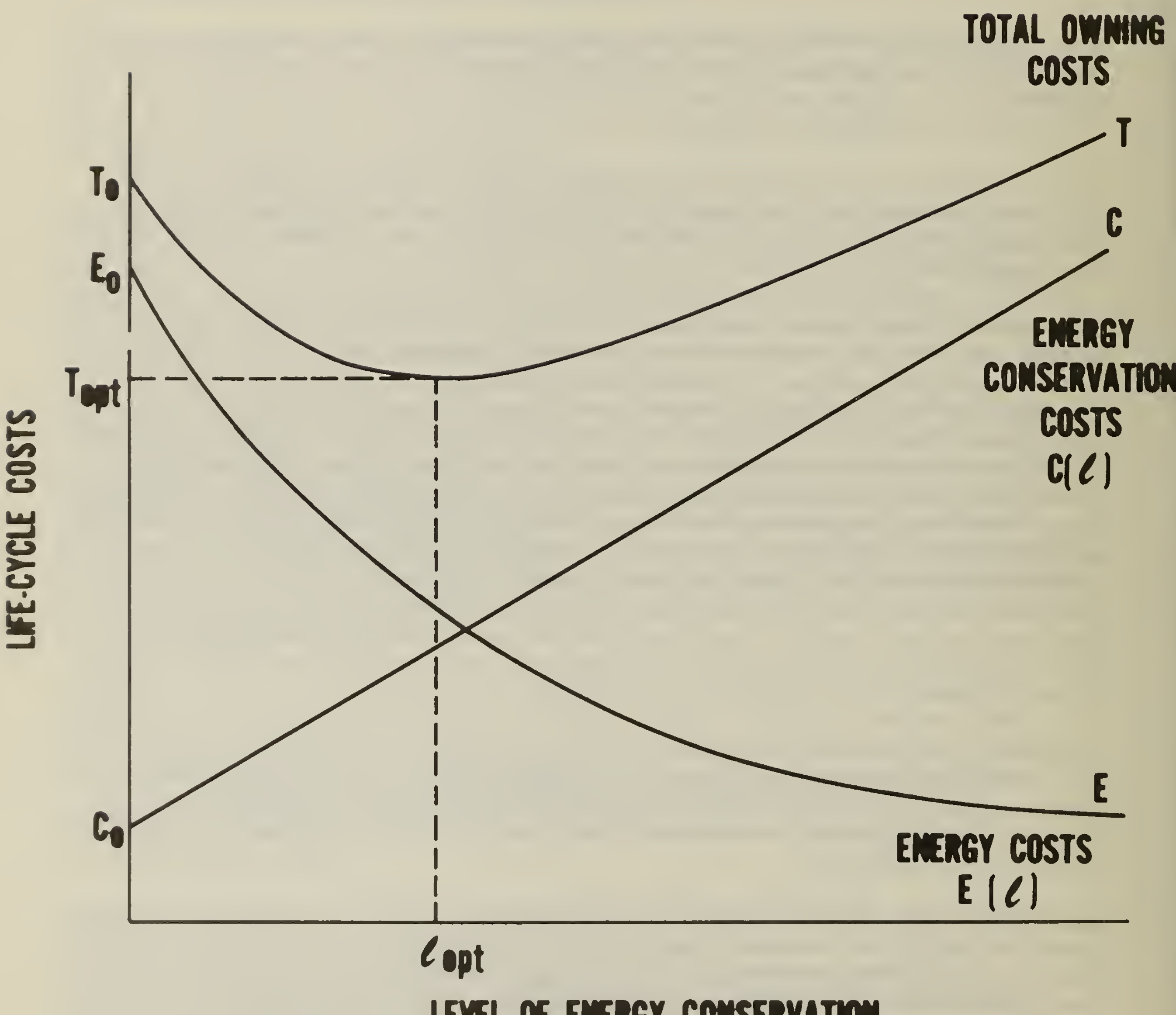
It was stated earlier that life-cycle cost techniques would be used in this study because they explicitly considered all costs over the study period. We now wish to examine how life-cycle cost techniques can be used to look at a weatherization investment from the viewpoint of the low-income homeowner.

As a homeowner increases the level of weatherization, the amount of money spent on energy is reduced. Energy losses, however, do not fall to zero. This is due to the non-linear (in this case inverse) relationship between heat losses and the level of weatherization. This relationship must be recognized and incorporated in the calculation of life-cycle energy costs. Referring to curve E_0E in Figure C.6, it can be seen that the life-cycle energy costs associated with no weatherization investment, E_0, are quite

---

[1] Based on the usual shape of the $S(\ell)$ and $C(\ell)$ curves, it is safe to assume that the second order condition for a maximum, $NS''(\ell) < 0$, is also satisfied.

FIGURE C.6 MINIMIZING LIFE-TIME BUILDING COSTS THROUGH OPTIMUM WEATHERIZATION



high. As the level of the energy conservation investment is increased, life-cycle energy costs fall off quickly at first and then at a diminishing rate. Of course, if we are to count the benefits of reduced energy consumption which accrue from weatherization we must also include all costs associated with that level of weatherization. These costs, the life-cycle costs of energy conservation are illustrated graphically by the curve C_oC on Figure C.6. Notice that the initial levels of weatherization are the most expensive due to set ups for labor and equipment. The C_oC curve then rises at a constant rate.

The homeowner must now decide how to tradeoff the costs of weatherization against reduced energy costs. If we vertically sum the two curves, we get the total life-cycle costs to the homeowner--that is, the costs both of the energy and of the weatherization options. Notice that this curve, T_oT, decreases to a minimum and then rises. At the minimum, T_{opt}, the total life-cycle costs to the homeowner are minimized. It is this level of weatherization, ℓ_{opt}, that is optimal for the homeowner because it minimizes the costs of owning and operating the system.[1] By a closer examination of the T_oT curve it can be seen that at any point to the left of the point (ℓ_{opt}, T_{opt}) total costs could be reduced by increasing the level of energy conservation. Similarly, at any point to the right of (ℓ_{opt}, T_{opt}), total costs could be reduced by reducing the level of energy conservation.

The criterion for maximizing the homeowners net savings will now be derived from Figure C.6. As a first step draw a horizontal line from E_o. The vertical distance from the horizontal line emanating from E_o to the E_oE curve, for any given ℓ, is then equal to the life-cycle energy savings of that level of weatherization. Denoting life-cycle energy costs, as a function of ℓ, as $E(\ell)$, life-cycle savings, $S(\ell)$, are then given by the following equation

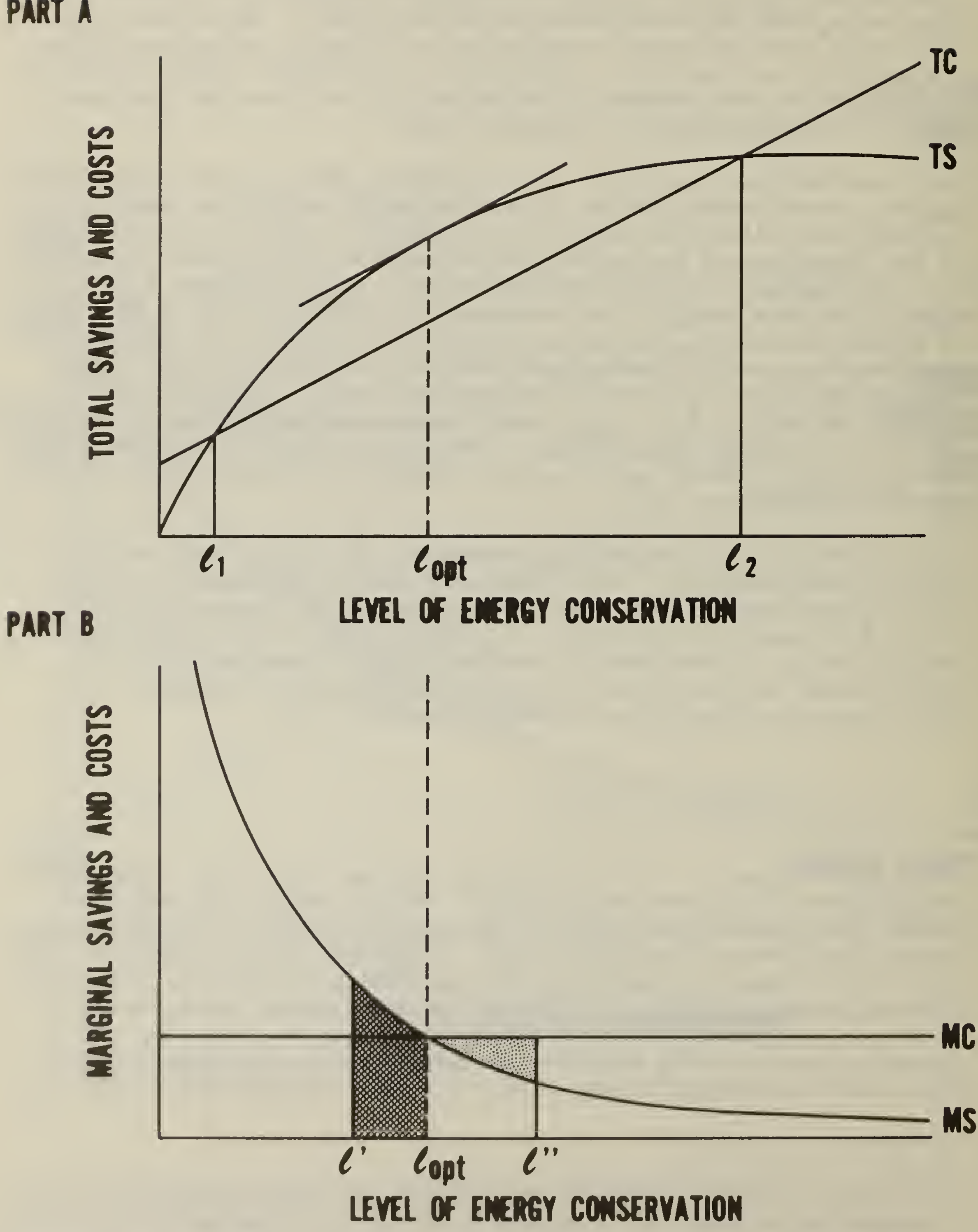
$$S(\ell) = E_o - E(\ell).$$

In Part A of Figure C.7 both life-cycle savings, $S(\ell)$, and energy conservation costs, $C(\ell)$, have been plotted. Notice that at all levels of energy conservation less than ℓ_1, the life-cycle costs of weatherization exceed the life-cycle energy savings. Similarly, at all levels of energy conservation above ℓ_2 the life-cycle costs of weatherization exceed the life-cycle energy savings. Therefore, weatherization is economically viable only at levels of energy conservation between ℓ_1 and ℓ_2. The number of years it will take for the weatherization investment to pay for itself will depend on what level of energy conservation between ℓ_1

---

[1] The term system as used here denotes both the energy purchased and the weatherization options. Implicit in the costs of owning and operating the system is the rate at which energy prices are expected to increase over the study period as well as the rate at which future costs and savings are to be discounted.

FIGURE C.7 OPTIMIZING A WEATHERIZATION INVESTMENT



and ℓ_2 is selected by the homeowner.[1] Although there are many levels of investment which pay for themselves, there is only one optimal level of investment. The optimal level of investment is the point at which net savings are maximized. Graphically it is the point where the vertical distance between the two curves (TS and TC) is maximized, that is, where the slope of the total savings curve is equal to the slope of the total cost curve. Note that this point does not guarantee a payback in say 11 years. In fact, when more than one option is being examined the payback periods on the optimal levels of investment are likely to vary considerably.

Let us now examine the marginal savings and marginal cost curves in Part B of Figure C.7. Since the life-cycle cost curve was assumed linear, marginal costs, MC, are constant. The rate of decline of the marginal savings curve, MS, however diminishes. This, once again, is a reflection of the fact that there is an inverse relationship between heat flows and the level of energy conservation.

The point at which MS crosses MC is revealed to be the optimal level of energy conservation. (See the dotted vertical line from the point of tangency in Part A of Figure C.7.) At all levels of energy conservation, ℓ', below ℓ_{opt}, life-cycle energy savings generated by the increment $\ell_{opt} - \ell'$ (shown cross hatched), exceed the life-cycle costs incurred by installing that increment (the rectangular part of the cross hatched area). Similarly, at all levels of energy conservation, ℓ'', above ℓ_{opt}, life-cycle energy savings generated by the increment $\ell'' - \ell_{opt}$ are less than the life-cycle costs incurred by that increment. The exact difference is equal to the area of the lightly shaded triangle in Part B of Figure C.7. Under the assumption of perfect information, homeowners would thus gravitate toward that level of energy conservation which eliminates any potential for further improvement through raising or lowering of the level of energy conservation.

The previous discussion focused on the case of an optimal level of weatherization using a given set of options. Increasing the level of weatherization could therefore mean either increasing the input of all weatherization options or adding one or more new options. To draw the analogy to the theory of the firm once more, suppose a firm produces one output but has many inputs; how does it combine these inputs so as to maximize its profits? We have already seen that the homeowner's net savings are directly analogous to the firm's profits. The question facing the homeowner therefore becomes, "How do I combine the weatherization options in such a manner that I maximize net savings?" In the discussion which follows it will be assumed that all weatherization options are independent. That is, any savings generated or costs incurred by increasing the level of one option does not affect those

---

[1] The number of years which it takes the present discounted value of weatherization savings to equal weatherization costs is defined as the payback period.

generated or incurred by any other option. This simplification permits us to treat both savings and costs as additive. To make this point more transparent, a slight modification in the notation for weatherization savings and costs is useful. If weatherization costs are denoted $C(\ell_1, \ell_2, \ldots, \ell_n)$ and weatherization savings as $S(\ell_1, \ell_2, \ldots, \ell_n)$ where the ℓ_i for i equal to 1, 2, ..., n indicate the respective weatherization options, then

$$C(\ell_1, \ell_2, \ldots, \ell_n) = C_1(\ell_1) + C_2(\ell_2) + \ldots + C_n(\ell_n)$$

and

$$S(\ell_1, \ell_2, \ldots, \ell_n) = S_1(\ell_1) + S_2(\ell_2) + \ldots + S_n(\ell_n)$$

where

$C_i(\ell_i)$ = the cost of the i^{th} option.

We now wish to examine how a homeowner should move toward an optimum. First let us assume that the homeowner has a binding budget constraint. Net savings must therefore be maximized subject to this budget constraint. In order to accomplish this task we shall make use of the method of Lagrangian Multipliers.

In this case we seek to maximize

$$S(\ell_1, \ldots, \ell_n) - C(\ell_1, \ldots, \ell_n)$$

subject to

$$C(\ell_1, \ldots, \ell_n) \leq B$$

where B is the budget constraint. We then define a new function, L, such that

$$L = [S(\ell_1, \ldots, \ell_n) - C(\ell_1, \ldots, \ell_n)] + \lambda[B-C(\ell_1, \ldots, \ell_n)]$$

where λ is an additional variable called the Lagrangian Multiplier. L is then maximized[1] by differentiating with respect to the ℓ_i for i equal from 1 to n, and also with respect to λ. The resultant derivatives are then set equal to zero.[2] Upon simplification we get

---

[1] Notice that since $B-C(\ell_1, \ldots, \ell_n) = 0$ at the highest allowable budget, L is equal to net savings.

[2] We are tacitly assuming that the second order conditions are satisfied. These conditions require the bordered Hessian matrix to be negative definite. See Eugene Silberberg, The Structure of Economics: A Mathematical Analysis, McGraw-Hill Book Company, New York, 1978.

$$\frac{S_1'(\ell_1)}{C_1'(\ell_1)} = 1 + \lambda, \ldots, \frac{S_n'(\ell_n)}{C_n'(\ell_n)} = 1 + \lambda$$

where $\lambda \geq 0$.[1]

That is, on a limited budget the weatherization options should be installed in such a way that the ratios of marginal savings to marginal cost for each option are equal. This point can be made more clear through reference to the marginal savings to marginal cost ratio. The ratio of marginal savings to marginal cost, $\frac{S_i'(\ell_i)}{C_i'(\ell_i)}$, shows the dollar amount of savings generated over the life cycle by an additional dollar investment in weatherization for a particular option. Consequently, if two options were being considered (both with marginal savings to marginal cost ratios greater than one) and one had a lower marginal savings to marginal cost ratio, it would be possible to transfer a dollar from the option with the lower ratio to the one with the higher ratio and increase net savings. Only when the marginal savings to marginal cost ratios are equal across all options is it no longer possible to trade dollars in one options for dollars in another. We may now explore how this information can be used to arrive at an optimal solution. In the previous example the Lagrangian multiplier, λ, was taken to be greater than or equal to 0. If λ is greater than 0, this implies that

$$S_i'(\ell_i) > C_i'(\ell_i) \qquad i = 1, \ldots, n.$$

Thus if the budget is increased a small amount, greater net savings can be achieved by increasing the level of the i^{th} option.

Consider for the moment the case of two weatherization options.[2] Given the above functional relationships, total savings and total costs associated with each level of weatherization can be calculated. Consequently, the net savings associated with each combination can be calculated. Furthermore, by reducing the level of one option and increasing the level of the other a small amount, the same net savings can be generated. For example, there exist many combinations of the two weatherization options which will produce a given amount of net savings. These iso-net savings curves[3] may be plotted graphically and used to identify an expansion path[4] along which the homeowner moves to achieve the optimum level of weatherization. Figure C.8 illustrates what such an expansion path would look like.

---

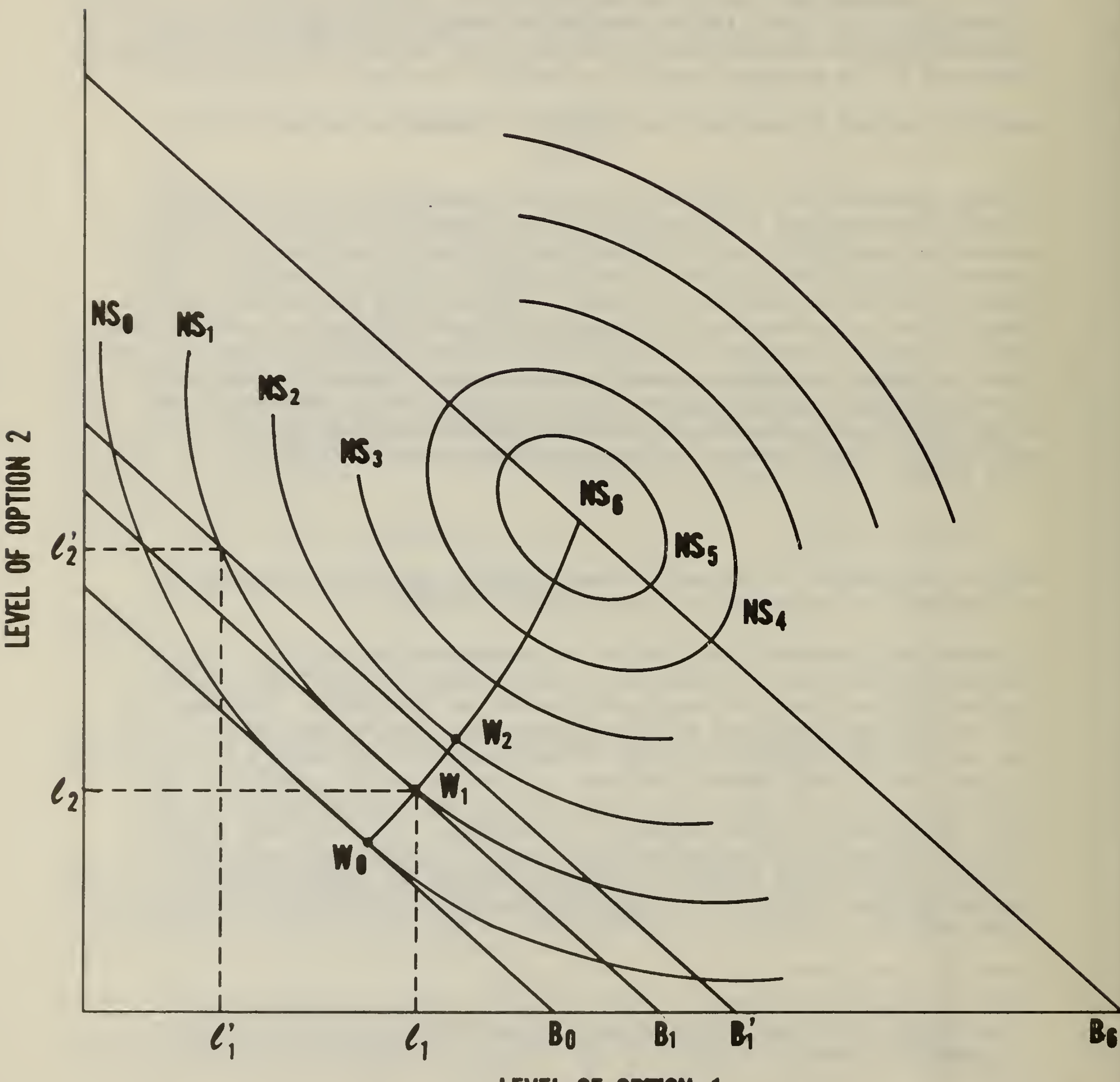
[1] The Lagrangian Multiplier, λ, will be greater than or equal to zero as long as it is profitable to use the entire budget, B, for weatherization.

[2] n is now equal to 2.

[3] The iso-net savings curve show all of the combinations of weatherization options 1 and 2 which result in the same net savings.

[4] Assuming the average costs of the two options remain the same, the expansion path shows the locus of cost minimizing choices facing the consumer as the available budget is increased. An excellent discussion of a firm's expansion path is given in Walter Nicholson, Microeconomic Theory: Basic Principles and Extensions, The Dryden Press, Inc., Hinsdale, Ill., 1972.

FIGURE C.8 OPTIMIZING WEATHERIZATION INVESTMENTS SUBJECT TO A BUDGET CONSTRAINT



The level of option 1 is plotted on the horizontal axis of Figure C.8 whereas the level of option 2 is plotted along the vertical axis. The iso-net savings curves are denoted as NS_o through NS_6. The iso-net savings curve NS_o is that combination of options 1 and 2 which produces no net savings. The iso-net savings curve NS_1, is that combination of options 1 and 2 which produce some specified positive net savings, say \$175. Notice that the least cost way of achieving NS_1 dollars of net savings is to spend B_1 dollars, where

$$B_1 = C_1(\ell_1^1) + C_2(\ell_2^1)$$

and ℓ_1^1 = the level of option 1; and

ℓ_2^1 = the level of option 2.

At this level of investment the budget curve is tangent to the iso-net savings curve at W_1, where the term W_1 is used to indicate the first weatherization package, combination of ℓ_1, and ℓ_2, which is being considered for installation. At this point the slope of the budget curve

$$\frac{C_1'(\ell_1^1)}{C_2'(\ell_1^1)}$$

is equal to the slope of the iso-net savings curve. This relationship produces the constrained maximum criterion,

$$\frac{S_1'(\ell_1^1)}{C_1'(\ell_1^1)} = \frac{S_2'(\ell_2^1)}{C_2'(\ell_2^1)} = k$$

where $S_i'(\ell_i^1)$ = marginal savings for option i;

$C_i'(\ell_i^1)$ = marginal cost for option i;

$k = 1 + \lambda.$

If the same net savings were realized with any other budget, say B_1', with levels $\ell_1^{1'}$ and $\ell_2^{1'}$ respectively, then from Figure C.3 it can be seen that budget B_1 is greater than B_1. Notice also that the iso-net savings curves curl back on themselves. That this occurs may be demonstrated by referring to Part A of Figure C.7 where it can be seen that increasing the level of energy conservation beyond a certain point (ℓ_2) generates increasingly higher costs while savings diminish. The locus of points at which the budget curves are tangent to the iso-net savings curves is the expansion path along which the homeowner moves to achieve the most weatherization per dollar spent. As the budget curves move out to the right, more money is being spent on weatherization. The budget is increased until when B_6 dollars are spent, the homeowner can achieve maximum net savings of NS_6 dollars, say \$2100, at point W_6 (the sixth weatherization package). At this point

$$\frac{S_1'(\ell_1^6)}{C_1'(\ell_1^6)} = \frac{S_2'(\ell_2^6)}{C_2'(\ell_2^6)} = k$$

as in the previous cases. However, in this case k is equal to 1, which implies

$$S_1'(\ell_1^6) = C_1'(\ell_1^6); \; S_2'(\ell_2^6) = C_2'(\ell_2^6)$$

This is the maximum efficiency criterion. Notice that if more than B_6 dollars are spent on weatherization, net savings are reduced.[1] The levels of weatherization that produced NS_6 dollars of net savings would therefore be optimal.

Let us now examine the impact that a payback constraint has on the optimum level of weatherization. Consider the case where we have four weatherization options. For each of these options the ratio of marginal savings to marginal costs,

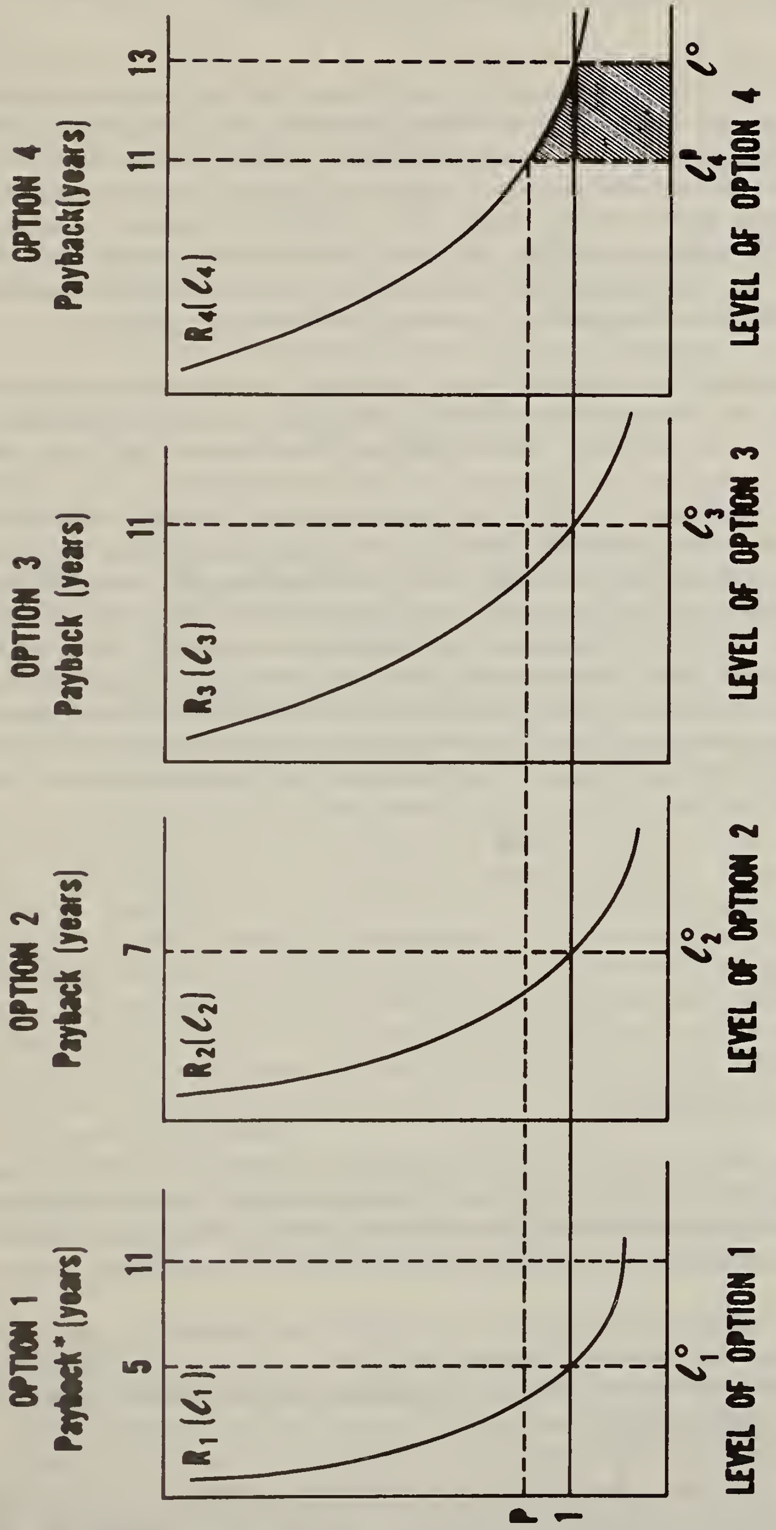
$$R_i(\ell_i) = \frac{S_i'(\ell_i)}{C_i'(\ell_i)} \quad \text{for } i = 1, 2, 3 \text{ and } 4$$

can be plotted graphically. From the preceding discussion, we know that the optimal level of weatherization consists of those levels, ℓ_i, where $R_i(\ell_i) = 1$ for i = 1, 2, 3 and 4.

In Figure C.9, $R_i(\ell_i)$ is plotted for each option. The level of weatherization is shown on the horizontal axis of each figure. The vertical axis shows the values which $R_i(\ell_i)$ takes on as ℓ_i varies. The horizontal line at $R_i(\ell_i) = 1$ shows the optimum level of weatherization for each option considered in isolation. A second horizontal axis is drawn on the top of each figure. The markings on this axis shows how long it takes the option to pay for itself as a function of the weatherization level. A quick examination of Figure C.9 shows that at the optimal level of weatherization option 1 takes 5 years to payback, option 2 takes 7 years, option 3 takes 11 years, and option 4 takes 13 years. Thus if an 11 year payback constraint is imposed on each option, as is done in the demonstration program, only option 4 fails. Now if the level of option 4 is reduced from ℓ_4^o to ℓ_4^p, where the p denotes payback, $R_4(\ell_4^p)$ is greater than 1. Let us denote this value as P. If ℓ_4^p units of option 4 are installed, life-cycle energy savings will be reduced from what they would have been at ℓ_4^o by an amount equal to the entire cross hatched area. Life-cycle costs however are only reduced by the rectangular area bounded above by the horizontal line at 1. The triangular area thus represents

[1] This would imply that λ is less than zero. The reader interested in a more mathematical discussion is referred to the text by Silberberg.

FIGURE C.9 EFFECT OF A PAYBACK CONSTRAINT ON OPTIMUM WEATHERIZATION LEVELS



* In actual practice the payback scale may not be linearly related to the level of the energy conservation investment.

foregone net savings. The imposition of a payback constraint therefore does not lead to a utility maximizing solution.[1,2]

The above illustration shows how the use of a payback constraint as an investment criterion produces an imbalance in the weatherization package. It is important to point out that if payback alone is used, the result is likely to be economically inefficient. From Figure C.9 it can be seen that increasing the level of weatherization to the point where the option just pays back in 11 years will result in costs that are not being offset by energy savings in two of the four cases (options 1 and 2). An additional disadvantage is that payback calculations ignore benefits which accrue to the homeowner beyond the eleventh year.

An alternative way to think of the payback constraint, and the one used in this study, is to treat it, where binding, in the same way that physical barriers are treated. For example, the amount of wall insulation which can be installed is limited to the thickness of the interior-exterior wall cavity. If R_i denotes the level of wall insulation then $R_i(\ell_i)$ would be greater than 1. In the presence of physical barriers, other economic studies have shown that it is sufficient to optimize the level of energy conservation for the options which are not affected by the presence of such a barrier.[3] We shall therefore proceed with the optimization of the other weatherization options in this manner. If a payback constraint is binding on one option, it will be noted and the economic analysis of the other options will proceed as if no budget constraint were imposed.

---

1 It is important to note that there may be instances where an 11 year payback constraint would not be binding on any option, since it would occur at a level where $R(\ell_i^o)$ was less than 1 for all i. In this case a utility maximizing solution would still be possible.

2 An alternative method would be to apply the payback constraint to the entire package of weatherization options. From an economic efficiency viewpoint this method would be preferred to an option application of the payback con[illegible]t.

3 Stephen R. Petersen, Retrofitting Existing Housing for Energy Conservation: An Economic Analysis, National Bureau of Standards, Building Science Series 64, December 1974.

APPENDIX D

DESCRIPTION OF COMPUTER PROGRAM USED TO MAKE ECONOMIC FORECASTS

CSAOWP (Community Services Administration Optimum Weatherization Package) is an interactive computer program developed by NBS and written in BASIC language[1] that determines the cost effectiveness of thirty-seven alternative weatherization options. Using a life-cycle benefits versus costs approach, the program calculates for each option the energy savings over 11 years and the energy savings over the life of the option (20 years was used in this analysis). Also included are the option cost over 11 years and the life-cycle cost of the option. Using these values, the program then calculates the savings-to-cost ratio of either the total present value costs and savings, or the marginal costs and savings in cases where the investment can be installed in incremental stages (for example, increasing thicknesses of insulation).

To facilitate the use of the program, and for ease in analyzing various combinations of fuel and housing types, a data file was set up for each of the 15 cities in the demonstration. The name of each file consists of the first two letters of the city name or a similar abbreviation. Corresponding to each city file is a specific code number (numbers 1 through 15, alphabetically) which is requested by the computer as the first input value. Two types of information are contained in these files. The first type consists of the weather data needed to calculate energy savings for the alternative weatherization options. These data include: DD_A[2], total degree days; DD_B, degree days for basement walls; DD_C, degree days occurring at night; DD_D, degree days occurring during the day; DD_E, degree days for the basement ceiling; and the number of heating days. The second type of information is a complete set of first costs for the architectural options, as described and listed in Appendix A. The program uses these figures to calculate the 11 year cost and total cost of each option over the study period, adjusting and discounting to include periodic replacement. The replacement schedule is based on that shown earlier in Table 4.1. The lifetime costs are used in the calculation of the savings-to-cost ratios, and the 11 year costs are used for determining if the payback criterion is satisfied.

After the user informs the computer for which city an analysis is desired, the program requests any additional information required to complete the economic calculations. The discount rate (real terms) and length

---

1 "BASIC" is an acronym for Beginners All-Purpose Symbolic Instruction Code. For a description of the use of BASIC see <u>BASIC LANGUAGE</u>, Honeywell Software Series 400, Honeywell Information Systems, Inc., August 1971.

2 The subscript refers to the variable name used in the computer program.

of study period are variable inputs. The fuel type can be fuel oil, natural gas, electricity, propane (bottled gas) or kerosene. The price per unit and fuel price escalation rate are then input so as to correspond to that fuel type. Three housing types are permitted: (1) frame, (2) masonry and (3) veneer.

From this information, the program computes the present value factors needed to make the energy savings calculations. The following formula[1] is used for both 11 and 20 years:

$$PVF = \frac{1 + P}{D - P} \left[1 - \left(\frac{1 + P}{1 + D}\right)^N\right] \times FP$$

where:

P = real rate of change in fuel prices

D = discount rate

N = number of years (11 and 20 in our case)

$$FP = \frac{100{,}000 \text{ Btu} \times \$/\text{unit}}{(\text{Btu content/unit}) \times (\text{Efficiency for the fuel type})}$$

The 11 year factor is used to determine if the savings from the option are sufficient to cover the cost of the option within 11 years. The 20 year (or lifetime) factor is used for calculating the savings-to-cost ratio, a measure which provides a way of ranking the options so that the most cost-effective package of options can be selected.

The annual savings for each option are then calculated using the equations described earlier in this report. The cost of the energy load of a category with the option installed is subtracted from the existing energy load cost (called BASE ENERGY COST in program). These savings are then multiplied by the 11 year and lifetime present value factors, and divided by 100,000 to get values (columns 11PVS and 20PVS in the program output) that can be compared with the corresponding costs (columns 11PVC and 20PVC). For certain types of options, the total savings and total costs are not as important as the additional savings and additional cost incurred by the installation of, say, an extra window covering or a thicker layer of insulation. For these categories, a marginal analysis is done. The change in cost and change in savings (column *20PVC and *20PVS) of going from one stage to the next are computed and are used in the savings-to-cost ratio.

Finally, the program calculates the savings-to-cost ratio for each of the options by dividing the 20 year present value savings by the 20 year present value costs (or marginal values as indicated above). All

---

[1] For further discussion of the use of this formula, see Section 3.2.

of these values are then printed in a table format, with the separate categories of options divided and each option labeled. Those options which are cost effective can be selected and ranked through a comaprison of ratios and by confirming that payback occurs within 11 years.

FIGURE D.1 FLOWCHART OF COMPUTER PROGRAM

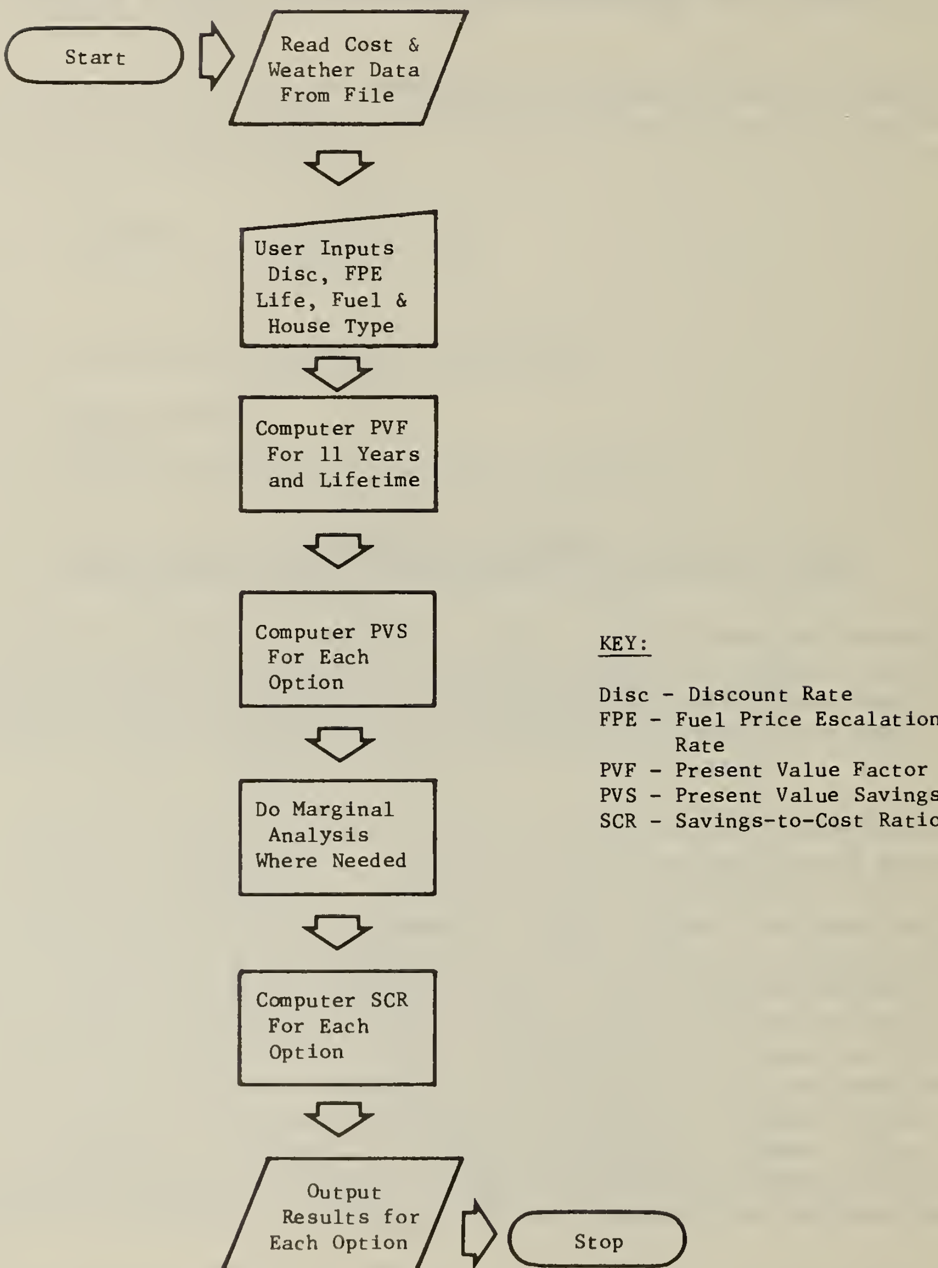


FIGURE D.1
FLOWCHART OF COMPUTER PROGRAM

APPENDIX E

SUMMARY OF BALANCE POINT CALCULATIONS FOR EACH DEMONSTRATION SITE

Tables E.1 through E.29 present the forecasts for the optimal level of weatherization for each demonstration site as a function of balance point. The range of variation in balance point is between 50°F and 70°F in increments of 2.5°F; in all, nine balance points are analyzed. These balance points are typical of those empirically estimated with actual energy consumption data. A separate table is presented for each city and each fuel type. It is important to point out that although these balance points correspond to those which were empirically estimated for the houses in the demonstration program, the weatherization packages which will actually be installed in those houses are presented in Tables 4.9, 4.10 and 4.11.

The heating balance point (average outside temperature in °F at which heating system comes on to maintain the interior thermostat setting) and the K-factor (rate at which the house consumes energy in Btu/degree day) were determined by NBS for each house in the demonstration, by applying standard correlation and regression techniques to fuel consumption and weather data. Given data on fuel consumption and on temperatures from the Weather Bureau, it is possible to plot fuel consumption versus local degree days for a specific time period. Different balance points result in different degree day totals for any periods in which temperatures fell below the balance point. Past studies have shown that finding the balance point which produces the best "fit" straight line to a fuel use temperature data plot will provide a good measure of space heating fuel consumption for a house.[1] From this information it is also possible to calculate the expected fuel consumption of the house for other time periods, from the temperature data for those time periods. The accuracy of the calculation is dependent on how closely the other variables associated with energy consumption, such as construction and thermostat setting, remain constant.

Figure E.1 is a sample computer printout of a balance point calculation. In this figure, T_o is the balance point of the house, B_1 is the slope or K-factor of the best fit line (least squares line), and B_o is the base load per degree day or that portion of the fuel consumption which can not be attributed to weather variations (including, in the sample case, the heating of service hot water through a "tankless coil" in the furnace).

---

[1] Mayer, L. S., and Y. Benjamin, "Modelling Residential Demand for National Gas as a Function of the Coldness of the Month," Energy in Buildings, Vol. VI, No. 3, April 1978.

FIGURE E.1 SAMPLE BALANCE POINT CALCULATION

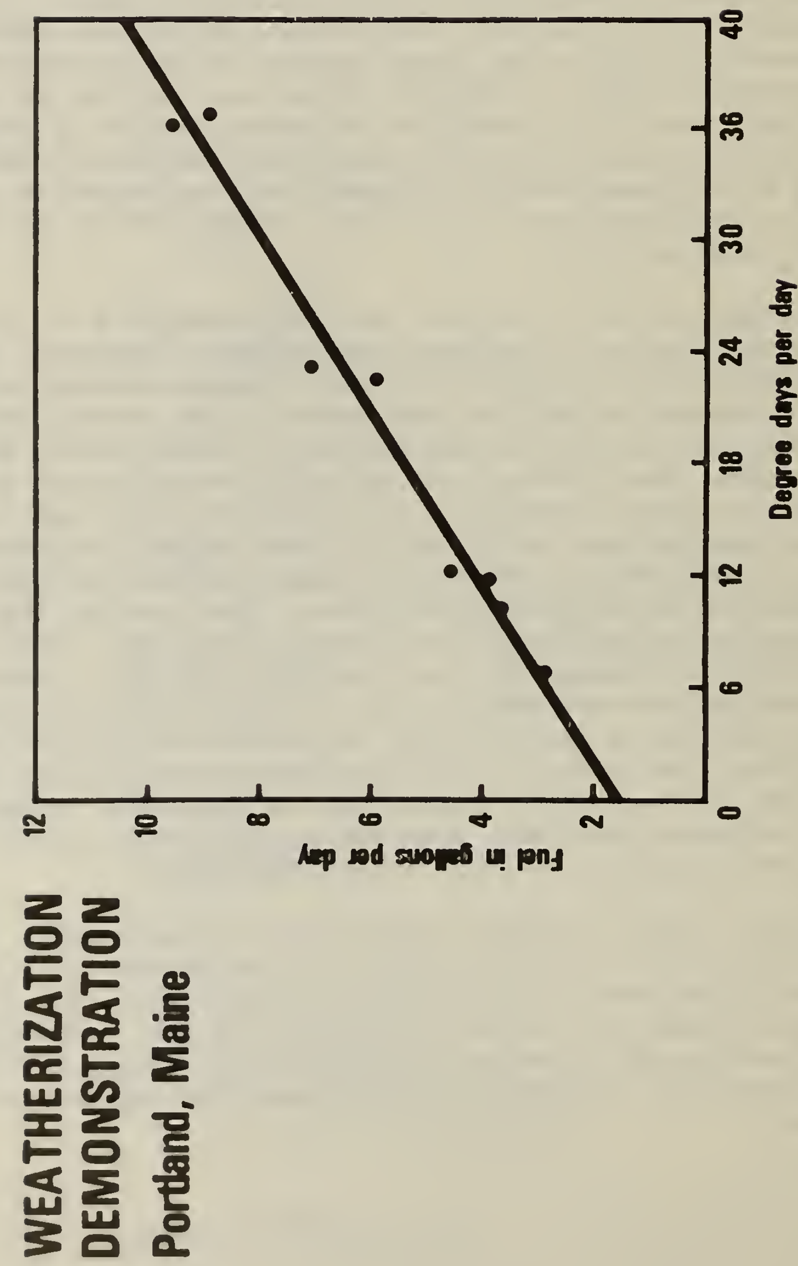


TABLE E.1 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN ALBUQUERQUE, NEW MEXICO

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing						X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows						X	X	X	X
Caulk Windows					X	X	X	X	X
Weatherstrip Doors						X	X	X	X
Caulk Doors						X	X	X	X
Weatherstrip Attic Hatch				X	X	X	X	X	X
WINDOWS									
Storm Windows					X	X	X		
Storm + Film									
Storm + Shutter									
Triple Glazing								X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)				X					
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X	X							
R-19 Insulation			X	X	X				
R-30 Insulation						X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation							X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.2 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN ATLANTA, GEORGIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass			X	X	X	X	X	X	X
Reset Glazing								X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows								X	X
Caulk Windows								X	X
Weatherstrip Doors									X
Caulk Doors									X
Weatherstrip Attic Hatch								X	X
WINDOWS									
Storm Windows									X
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation			X	X	X				
R-19 Insulation						X	X	X	
R-30 Insulation									X
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.3 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR PROPANE IN ATLANTA, GEORGIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing			X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows				X	X	X	X	X	X
Caulk Windows				X	X	X	X	X	X
Weatherstrip Doors				X	X	X	X	X	X
Caulk Doors				X	X	X	X	X	X
Weatherstrip Attic Hatch			X	X	X	X	X	X	X
WINDOWS									
Storm Windows				X	X				
Storm + Film									
Storm + Shutter									
Triple Glazing						X	X	X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)							X	X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X								
R-19 Insulation		X	X						
R-30 Insulation				X	X	X	X	X	
R-38 Insulation									X
WALLS									
R-11 Insulation						X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.4 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN CHARLESTON, SOUTH CAROLINA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass				X	X	X	X	X	X
Reset Glazing									X
Install New Threshold			X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows									
Caulk Windows									X
Weatherstrip Doors									
Caulk Doors									X
Weatherstrip Attic Hatch									X
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation				X	X	X	X	X	
R-19 Insulation									X
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.5 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN CHARLESTON, SOUTH CAROLINA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass			X	X	X	X	X	X	X
Reset Glazing							X	X	X
Install New Threshold		X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows								X	X
Caulk Windows							X	X	X
Weatherstrip Doors									X
Caulk Doors								X	X
Weatherstrip Attic Hatch							X	X	X
WINDOWS									
Storm Windows									X
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation			X	X	X	X	X		
R-19 Insulation								X	X
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.6 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR ELECTRICITY IN CHARLESTON, SOUTH CAROLINA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing					X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows					X	X	X	X	X
Caulk Windows					X	X	X	X	X
Weatherstrip Doors						X	X	X	X
Caulk Doors					X	X	X	X	X
Weatherstrip Attic Hatch					X	X	X	X	X
WINDOWS									
Storm Windows							X	X	
Storm + Film									
Storm + Shutter									X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X	X	X	X					
R-19 Insulation					X	X	X		
R-30 Insulation								X	X
R-38 Insulation									
WALLS									
R-11 Insulation							X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.7 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR PROPANE IN CHARLESTON, SOUTH CAROLINA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass		X	X	X	X	X	X	X	X
Reset Glazing						X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows							X	X	X
Caulk Windows						X	X	X	X
Weatherstrip Doors							X	X	X
Caulk Doors						X	X	X	X
Weatherstrip Attic Hatch						X	X	X	X
WINDOWS									
Storm Windows								X	X
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation		X	X	X	X				
R-19 Insulation						X	X	X	
R-30 Insulation									X
R-38 Insulation									
WALLS									
R-11 Insulation									X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.8 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN CHICAGO, ILLINOIS

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors		X	X	X	X	X	X	X	X
Caulk Doors		X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows					X	X	X	X	
Storm + Film									
Storm + Shutter									X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation	X	X							
R-30 Insulation			X	X	X	X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation							X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.9 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN CHICAGO, ILLINOIS

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows		X	X	X					
Storm + Film									
Storm + Shutter					X	X	X	X	X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "							X	X	X
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X	X	X	X	X	X	
R-38 Insulation									X
WALLS									
R-11 Insulation				X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.10 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN COLORADO SPRINGS, COLORADO

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing							X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows							X	X	X
Caulk Windows		X	X	X	X	X	X	X	X
Weatherstrip Doors									X
Caulk Doors			X	X	X	X	X	X	X
Weatherstrip Attic Hatch						X	X	X	X
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X								
R-19 Insulation		X	X	X					
R-30 Insulation					X	X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.11 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR PROPANE IN COLORADO SPRINGS, COLORADO

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors		X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows		X	X						
Storm + Film									
Storm + Shutter				X	X	X	X	X	X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)				X	X	X	X		
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)								X	X
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X						
R-38 Insulation				X	X	X	X	X	X
WALLS									
R-11 Insulation			X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.12 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN EASTON, PENNSYLVANIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows		X	X	X					
Storm + Film									
Storm + Shutter									
Triple Glazing					X	X	X	X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)								X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation	X	X	X						
R-30 Insulation				X	X	X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation				X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.13 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN EASTON, PENNSYLVANIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows	X	X	X						
Storm + Film									
Storm + Shutter									
Triple Glazing				X	X	X	X	X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)								X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation	X	X							
R-30 Insulation			X	X	X	X	X	X	
R-38 Insulation									X
WALLS									
R-11 Insulation			X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.14 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN FARGO, NORTH DAKOTA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing	X	X	X	X	X	X			
Triple + Shutter							X	X	X
DOORS									
Storm Door (60% Glass)									
Second Wood Door "	X	X	X	X					
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "					X	X	X	X	X
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X	X	X				
R-38 Insulation						X	X	X	X
WALLS									
R-11 Insulation	X	X	X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.15 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN FARGO, NORTH DAKOTA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing	X	X	X	X	X				
Triple + Shutter						X	X	X	X
DOORS									
Storm Door (60% Glass)									
Second Wood Door "	X	X	X						
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "				X	X	X	X	X	X
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X	X					
R-38 Insulation					X	X	X	X	X
WALLS									
R-11 Insulation	X	X	X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	2	2	2	2	2	2	2	2	2

*Key for Basement Walls

A - Above Grade

TABLE E.16 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN LOS ANGELES, CALIFORNIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass							X	X	X
Reset Glazing									
Install New Threshold						X	X	X	X
Seal Structural Cracks			X	X	X	X	X	X	X
Weatherstrip Windows									X
Caulk Windows									X
Weatherstrip Doors									
Caulk Doors									X
Weatherstrip Attic Hatch									
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation							X	X	
R-19 Insulation									X
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation									

*Key for Basement Walls

A - Above Grade

TABLE E.17 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN MIAMI, FLORIDA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass									
Reset Glazing									
Install New Threshold									
Seal Structural Cracks					X	X	X	X	X
Weatherstrip Windows									
Caulk Windows									
Weatherstrip Doors									
Caulk Doors									
Weatherstrip Attic Hatch									
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation									

*Key for Basement Walls

A - Above Grade

TABLE E.18 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR ELECTRICITY IN MIAMI, FLORIDA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass									
Reset Glazing									
Install New Threshold							X	X	X
Seal Structural Cracks			X	X	X	X	X	X	X
Weatherstrip Windows									
Caulk Windows									
Weatherstrip Doors									
Caulk Doors									
Weatherstrip Attic Hatch									
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									X
R-19 Insulation									
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation									

*Key for Basement Walls

A - Above Grade

TABLE E.19 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN MINNEAPOLIS/ST. PAUL, MINNESOTA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows		X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows				X	X	X	X		
Storm + Film									
Storm + Shutter								X	X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "								X	X
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X							
R-38 Insulation			X	X	X	X	X	X	X
WALLS									
R-11 Insulation					X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.20 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN MINNEAPOLIS/ST. PAUL, MINNESOTA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows	X								
Storm + Film									
Storm + Shutter		X	X	X	X	X	X	X	X
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "			X	X	X				
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "						X	X	X	X
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation									
R-38 Insulation	X	X	X	X	X	X	X	X	X
WALLS									
R-11 Insulation	X	X	X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.21 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN OAKLAND, CALIFORNIA

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass							X	X	X
Reset Glazing									
Install New Threshold					X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows									
Caulk Windows									
Weatherstrip Doors									
Caulk Doors									
Weatherstrip Attic Hatch									
WINDOWS									
Storm Windows									
Storm + Film									
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation					X	X	X		
R-19 Insulation								X	X
R-30 Insulation									
R-38 Insulation									
WALLS									
R-11 Insulation									
BASEMENT WALLS*									
R-7 Insulation									

*Key for Basement Walls

A - Above Grade

TABLE E.22 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN PORTLAND, MAINE

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing	X	X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors	X	X	X	X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch	X	X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows	X								
Storm + Film									
Storm + Shutter									
Triple Glazing		X	X	X	X	X	X		
Triple + Shutter								X	X
DOORS									
Storm Door (60% Glass)									
Second Wood Door "				X	X	X			
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "							X	X	X
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X	X	X	X	X		
R-38 Insulation								X	X
WALLS									
R-11 Insulation	X	X	X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.23 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN ST. LOUIS, MISSOURI

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing		X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows								X	X
Caulk Windows		X	X	X	X	X	X	X	X
Weatherstrip Doors									X
Caulk Doors			X	X	X	X	X	X	X
Weatherstrip Attic Hatch						X	X	X	X
WINDOWS									
Storm Windows				X	X	X	X		
Storm + Film									
Storm + Shutter									
Triple Glazing								X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)									
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X	X							
R-19 Insulation			X	X	X	X			
R-30 Insulation							X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation							X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.24 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR NATURAL GAS IN TACOMA, WASHINGTON

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing				X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows			X	X	X	X	X	X	X
Caulk Windows			X	X	X	X	X	X	X
Weatherstrip Doors					X	X	X	X	X
Caulk Doors		X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch			X	X	X	X	X	X	X
WINDOWS									
Storm Windows					X	X	X		
Storm + Film									
Storm + Shutter									
Triple Glazing								X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)								X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X	X							
R-19 Insulation			X	X					
R-30 Insulation					X	X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation						X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.25 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN TACOMA, WASHINGTON

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing			X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows			X	X	X	X	X	X	X
Caulk Windows		X	X	X	X	X	X	X	X
Weatherstrip Doors				X	X	X	X	X	X
Caulk Doors		X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch		X	X	X	X	X	X	X	X
WINDOWS									
Storm Windows				X	X				
Storm + Film									
Storm + Shutter									
Triple Glazing						X	X	X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)							X	X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X								
R-19 Insulation		X	X						
R-30 Insulation				X	X	X	X		
R-38 Insulation								X	X
WALLS									
R-11 Insulation					X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.26 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR ELECTRICITY IN TACOMA, WASHINGTON

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing				X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows				X	X	X	X	X	X
Caulk Windows			X	X	X	X	X	X	X
Weatherstrip Doors					X	X	X	X	X
Caulk Doors		X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch				X	X	X	X	X	X
WINDOWS									
Storm Windows					X	X	X		
Storm + Film									
Storm + Shutter									
Triple Glazing								X	X
Triple + Shutter									
DOORS									
Storm Door (60% Glass)								X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation	X	X							
R-19 Insulation			X	X					
R-30 Insulation					X	X	X	X	X
R-38 Insulation									
WALLS									
R-11 Insulation					X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.27 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR FUEL OIL IN WASHINGTON, D.C.

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing		X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors				X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch				X	X	X	X	X	X
WINDOWS									
Storm Windows	X	X	X	X	X	X	X		
Storm + Film								X	X
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)							X	X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation	X								
R-30 Insulation		X	X	X	X	X	X		
R-38 Insulation								X	X
WALLS									
R-11 Insulation					X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.28 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR PROPANE IN WASHINGTON, D.C.

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing				X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows			X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors						X	X	X	X
Caulk Doors		X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch						X	X	X	X
WINDOWS									
Storm Windows	X	X	X						
Storm + Film				X	X	X	X	X	X
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)				X	X	X			
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)							X	X	X
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation									
R-30 Insulation	X	X	X	X					
R-38 Insulation					X	X	X	X	X
WALLS									
R-11 Insulation		X	X	X	X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

TABLE E.29 OPTIMAL WEATHERIZATION PACKAGES AS A FUNCTION OF BALANCE POINT FOR KEROSENE IN WASHINGTON, D.C.

INFILTRATION	50°F	52.5°F	55°F	57.5°F	60°F	62.5°F	65°F	67.5°F	70°F
Replace Broken Glass	X	X	X	X	X	X	X	X	X
Reset Glazing		X	X	X	X	X	X	X	X
Install New Threshold	X	X	X	X	X	X	X	X	X
Seal Structural Cracks	X	X	X	X	X	X	X	X	X
Weatherstrip Windows	X	X	X	X	X	X	X	X	X
Caulk Windows	X	X	X	X	X	X	X	X	X
Weatherstrip Doors				X	X	X	X	X	X
Caulk Doors	X	X	X	X	X	X	X	X	X
Weatherstrip Attic Hatch				X	X	X	X	X	X
WINDOWS									
Storm Windows	X	X	X	X	X	X			
Storm + Film							X	X	X
Storm + Shutter									
Triple Glazing									
Triple + Shutter									
DOORS									
Storm Door (60% Glass)							X	X	X
Second Wood Door "									
New Insulating Door "									
Storm Door (30% Glass)									
Second Wood Door "									
New Insulating Door "									
ATTIC									
R-11 Insulation									
R-19 Insulation	X								
R-30 Insulation		X	X	X	X	X	X		
R-38 Insulation								X	X
WALLS									
R-11 Insulation					X	X	X	X	X
BASEMENT WALLS*									
R-7 Insulation	A	A	A	A	A	A	A	A	A

*Key for Basement Walls

A - Above Grade

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBSIR 79-1948

2. Gov't. Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Optimizing Weatherization Investments in Low-Income Housing: Economic Guidelines and Forecasts

5. Publication Date
February 1980

6. Performing Organization Code

7. AUTHOR(S)
Robert E. Chapman, Richard W. Crenshaw, Kimberly A. Barnes, Phillip T. Chen

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)
Community Services Administration
1200 19th Street, N.W.
Washington, D.C. 20506

13. Type of Report & Period Covered
Final

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This study establishes a framework for systematically analyzing the economic viability of alternative methods of weatherizing low-income housing. These methods include, but are not limited to insulation, weatherstripping and caulking, and installation of storm windows and doors. The economic framework is illustrated through the development of a series of forecasts (economic guidelines) which show the optimal level of weatherization for low-income residences in 15 cities across the nation. These economic guidelines are designed to assist the Community Services Administration in carrying out its Weatherization Demonstration Program. In particular, they are designed to achieve a more balanced level of weatherization per dollar spent. The optimal level of weatherization is balanced in the sense that for a given weatherization budget no increases in net savings (total savings minus total costs) can be achieved by trading one method for another.

17. KEY WORDS (six to twelve entries, alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)
Benefit-cost analysis; building economics; building envelope; economic analysis; economic efficiency; energy conservation; insulation; life-cycle costs; low-income housing; marginal analysis; thermal efficiency; weatherization.

18. AVAILABILITY ☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Sup. of Doc., U.S. Government Printing Office, Washington, DC 20402, SD Stock No. SN003-003-

☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PRINTED PAGES

22. Price
$11.[illegible]

USCOMM-DC